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# AIRCREW OXYGEN SYSTEM DEVELOPMENT LABORATORY BREADBOARD SYSTEM TEST REPORT

by

R. J. Kiraly, J. D. Powell,  
R. G. Huebscher and A. D. Babinsky

PREPARED UNDER CONTRACT NO. NAS 2-4444

BY

**TRW** INC.  
CLEVELAND, OHIO

FOR  
AMES RESEARCH CENTER  
NATIONAL AERONAUTICS AND  
SPACE ADMINISTRATION

July 1970

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**TRW**  
MECHANICAL PRODUCTS DIVISION



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## FOREWORD

The development work described herein, which was conducted by the Mechanical Products Division of TRW Inc., was performed under NASA Contract NAS2-4444. R. J. Kiraly directed the system design and test as well as the development of the various system mechanical components. Instrumentation and controls development was headed by J. D. Powell. In its final configuration, the system used the Design II CO<sub>2</sub> Concentrator as developed by R. G. Huebscher. The overall aircrew oxygen system development program was directed by A. D. Babinsky. The contract technical monitor was P. D. Quattrone, Biotechnology Division, NASA Ames Research Center, Moffett Field, California.

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## SUMMARY

A closed loop, aircrew oxygen system was designed and a laboratory breadboard version of the system was constructed and tested. The system was designed for a one-man capacity. The system utilized water electrolysis as the oxygen generation subsystem and a hydrogen depolarized carbon dioxide concentrator as the carbon dioxide removal device in a closed rebreather loop.

An estimate was made of the size and weight of the NAOS system for a fully-developed prototype packaged version. It was estimated that a one-man system would occupy approximately 1/2 cu. ft. volume and the system would weigh less than 50 pounds. A mock-up of an engineering prototype was fabricated to demonstrate the packaging capability of the system.

Preliminary to the actual integration of the laboratory breadboard system, the major subsystems were assembled and checked out prior to the final assembly of the laboratory breadboard. Except for the electrochemical components and the electronic controls, all of the other components in the laboratory breadboard system were off-the-shelf, commercially available items. The laboratory breadboard was essentially a duplication of two previously designed and operated test rigs. These were the electrolysis module test rig and the carbon dioxide concentrator test rig. Each of these rigs had their own controls and instrumentation for operating the two electrochemical components. Interconnecting these two rigs and adding the rebreather system and a breathing simulator, completed the laboratory breadboard system.

Prior to the system tests, endurance tests on the two electrochemical components were conducted. Over 1500 hours of operation on the electrolysis module and over 500 hours of operation of the carbon dioxide concentrator were performed prior to the system integration tests. Start-up tests, steady state operation under varying breathing rates and volumes, and off-design tests were conducted with a complete laboratory breadboard system. In all of the tests conducted, the system met the performance specifications. Satisfactory operation of this system indicates that the system is feasible and can be developed into a prototype system.

## INTRODUCTION

TRW, under NASA Contract NAS2-4444, developed an aircrew oxygen system using electrochemical oxygen generation and carbon dioxide removal. The objective of the program was to develop a feasibility demonstration model of a safe, reliable, compact system which could replace the presently used LOX systems.

Aircraft oxygen systems are currently limited to the use of stored supplies of oxygen in the form of liquid oxygen or high pressure gaseous oxygen. Use of oxygen from these sources limits the duration of a mission to the amount of stored gases and creates somewhat of a problem in logistics and service to provide the needed oxygen.

A means of avoiding these problems is the provision of a method of continuously generating oxygen on board the aircraft as oxygen is required. This can be accomplished electrochemically by electrolysis of water or concentration of oxygen from the ambient air. The size and power requirements of these electrochemical oxygen generators would be large when coupled to an open loop aircraft oxygen system. If, however, a rebreather loop is provided such that the oxygen used corresponds to the pilot's metabolic consumption, the size of the oxygen generator and rebreather loop becomes competitive with a present-day LOX converter system. The rebreather loop functions to recondition the exhaled gases such that it can be reused in the breathing cycle. The rebreather thus removes exhaled carbon dioxide, nitrogen, water vapor and heat.

This report describes the system design, component design, testing and Laboratory Breadboard System (LBS) tests. The design and component testing of two major components, the Water Electrolysis Module (WEM) and the Carbon Dioxide Concentrator Module (CDCM) are described in separate reports, NASA CR-73394 and NASA CR-73397.

The LBS demonstrated the general feasibility of electrochemically providing oxygen and removing carbon dioxide in a closed loop aircrew oxygen system. Operation of this system was the first practical demonstration of such a system. The versatility of the LBS was further demonstrated by operation of the system in a manned open loop mode using a diluter demand regulator.

Preliminary endurance tests of both the WEM and CDCM were conducted on the LBS before the system was ready for completely integrated operation. Automatic current control for both modules was used in this testing. The LBS tests included various emergency operating modes. Test results were used in the redesign and packaging of the Flight Breadboard System (FBS).

## SYSTEM DESIGN

This section describes the efforts to arrive at a satisfactory oxygen system design. Starting with the establishment of design criteria, an initial system design was performed. System and component analyses of the initial design resulted in a more complete system definition. The system integration aspects were examined and, based on the overall performance requirements, a set of component specifications were established to guide the initial component design and development. Also, as a part of the system design effort, an estimation of the projected size and weight of a prototype system was made. Based on these projections, an engineering mock-up was designed and fabricated to illustrate the size and configuration of a prototype system.

### Design Criteria

The design objectives for NAOS (NASA Aircrew Oxygen System) were to obtain a safe, reliable system of low weight and size which would eliminate the need for ground support facilities and minimize the time and effort for maintenance. Studies at TRW prior to this program have shown that a system using the electrolysis of water to generate breathing oxygen and an electrochemical device to remove the carbon dioxide from a closed breathing system would best meet these objectives. The only periodic servicing required is to refill a water reservoir between flights. The system being a closed loop requires the generation of oxygen at a rate equal to that metabolically consumed by the user and losses due to leakage and venting.

The system design specifications were based upon the physiological requirements of a pilot. The breathing loop preliminary design requirements are outlined in Table I which also shows the basis for the requirements. These requirements were for the first phase program only, and were revised and expanded in the later phases of the NAOS development.

Table II lists the design goals for a fully-developed NAOS prototype. It was intended to use the F-111 aircraft requirements for flight profile, space availability and services on board as a design guide. However, this information was not available at the time the preliminary design guides of Table II were developed. Since this information was not critical to the first phase efforts in the program and since the requirements may change in the future, some assumptions were made in the design of the system. Some of these pertain to the availability of electrical power, compressed air for operation of the counter-lung, and liquid coolants for heat exchangers. Also, as shown in Table II, system volume was to be minimized but no maximum dimension had been established for packaging.

Upon reviewing the F-111 manuals obtained through NASA Ames, it became apparent that any future packaging considerations must be worked out with the aircraft designers. The oxygen subsystem should not be considered independently from the design of the other aircraft subsystems since packaging, location and performance of the oxygen system may affect other subsystems and should not be considered separately. It would be very difficult, based on the information we now have, to define space or a location for the NAOS system on the F-111.

TABLE I

## BREATHING LOOP DESIGN REQUIREMENTS

<u>Requirement</u>	<u>Basis for Requirement</u>
1. Pilot's oxygen consumption - 0.10 lb/hr	Based on data for light work typical of piloting aircraft
2. Electrolysis cell oxygen flow rate - 0.15 lb/hr	Pilot's consumption plus 0.05 lb/hr for CO <sub>2</sub> concentrator consumption
3. Pilot's respiratory minute volume - 0.5 CFM (14 liters/min)	Typical for light work, also actual measurements on pilots
4. Peak instantaneous respiratory flow rate - 1.6 CFM	Assumes sinusoidal respiratory flow
5. Pilot's tidal volume - 0.78 liters	Based on tests, varies with individuals
6. Temperature of breathing oxygen to pilot - 60°F to 90°F (70°F - 80°F preferable)	Comfort
7. Relative humidity of breathing oxygen to pilot - 50% maximum	Comfort
8. Breathing loop absolute pressure levels 3 psia to 15 psia	Sea level to physiological minimum safe pressure
9. CO <sub>2</sub> concentration in breathing oxygen to pilot - 1% by volume maximum at one atmosphere (7.6mm Hg vapor pressure maximum)	Well under safe maximum
10. CO <sub>2</sub> production by pilot - 0.12 lb/hr nominal	Metabolically consistent with oxygen consumption
11. Operating duration - 10 hours	Typical oxygen capacity of existing systems



TABLE II

F-111 OXYGEN SYSTEM DESIGN GOALS  
(First NAOS Prototype)

Oxygen Generating Capacity	0.20 lb/hr
Oxygen Purity	99.5% (dry), BB-0-925a
Oxygen Supply Pressure	65 psig
Oxygen Flow Rate to Pilot, average	0.5 CFM
Oxygen Temperature to Pilot	60°F to 90°F
Peak Respiratory Flow Rate	1.6 CFM
Oxygen Relative Humidity	50% maximum
System Operating Time	10 hours (+25% reserve)
Turn-Around Time	5 minutes - water refill
System Volume	< 1 ft <sup>3</sup>
System Weight	≤ 50 lb
System Power	< 700 watts
Rebreather Loop Pressure	F-111 cabin pressure plus specified pressure breathing schedule

The NAOS system, however, is quite flexible for packaging since the oxygen generating network, electrical network, and the rebreather network can be separated and interconnected by tubing and electrical cables.

At present the F-111 does not have a liquid coolant system. Liquid coolants would be desirable since the carbon dioxide concentrator, electrolysis module, electronics package, and heat exchanger would be more compact with a liquid coolant as compared to an air cooling system which requires ducting and finning for heat removal. From a system viewpoint, the addition of a liquid cooling system incorporating a pump and an air to liquid heat exchanger may result in a better overall system than using an air coolant with associated larger components and cooling air ducting. Again, these considerations must be dealt with in conjunction with the overall aircraft subsystems design.

### Initial System Design

The initial system design was based upon the criteria outlined in the previous section; specifically Table I. Figure 1 shows the components and their placement to meet the design criteria. A blower circulates breathing oxygen through the carbon dioxide concentrator which removes the carbon dioxide from the circulating flow and transfers it to the hydrogen stream on the opposite side of the concentrator module. The pilot's expiration enters the counter-lung which accommodates the pilot's tidal volume during breathing to maintain the loop at constant pressure during the breathing cycle. Inhalation oxygen is drawn from the circulating loop through a heat exchanger used as a dehumidifier.

This is required because the gas flow in the circulating loop will have a temperature about 120°F and nearly saturated with water vapor. A separator downstream of the dehumidifier removes the condensed water and directs it to a water vent which vents the water from the breathing loop. Oxygen from the electrolysis module enters through the demand regulator to make up the oxygen consumed by the pilot, the carbon dioxide concentrator, and system venting. Next, the oxygen is heated to a comfortable level for breathing by the pilot. During inhalation, the counter-lung is collapsed allowing this gas to enter the circulating loop.

Check valves in the mask maintain the inspiration and expiration flows in the proper direction. The check valve in the recirculating loop prevents "short circuiting" in the breathing loop.

This system can provide pressure breathing, that is, the breathing loop pressure can be above the cabin pressure. This would be required at cabin altitudes above 38,000 feet. The pressure breathing control will maintain the breathing loop pressure constant at 3 psia at altitudes between 38,000 and 43,000 feet. Above 43,000 feet, loop pressure will remain at 18 inches of water above ambient pressure. At cabin altitudes above 43,000 feet, pressure suits are required. Pressure breathing is accomplished by using air to pressurize the outside of the breathing bag in the counter-lung. This pressure is regulated by an aneroid device similar to those employed in pressure breathing demand oxygen regulators.

Denitrogenation is necessary to remove the nitrogen from the breathing loop. The nitrogen is eliminated from the body due to the partial pressure gradients

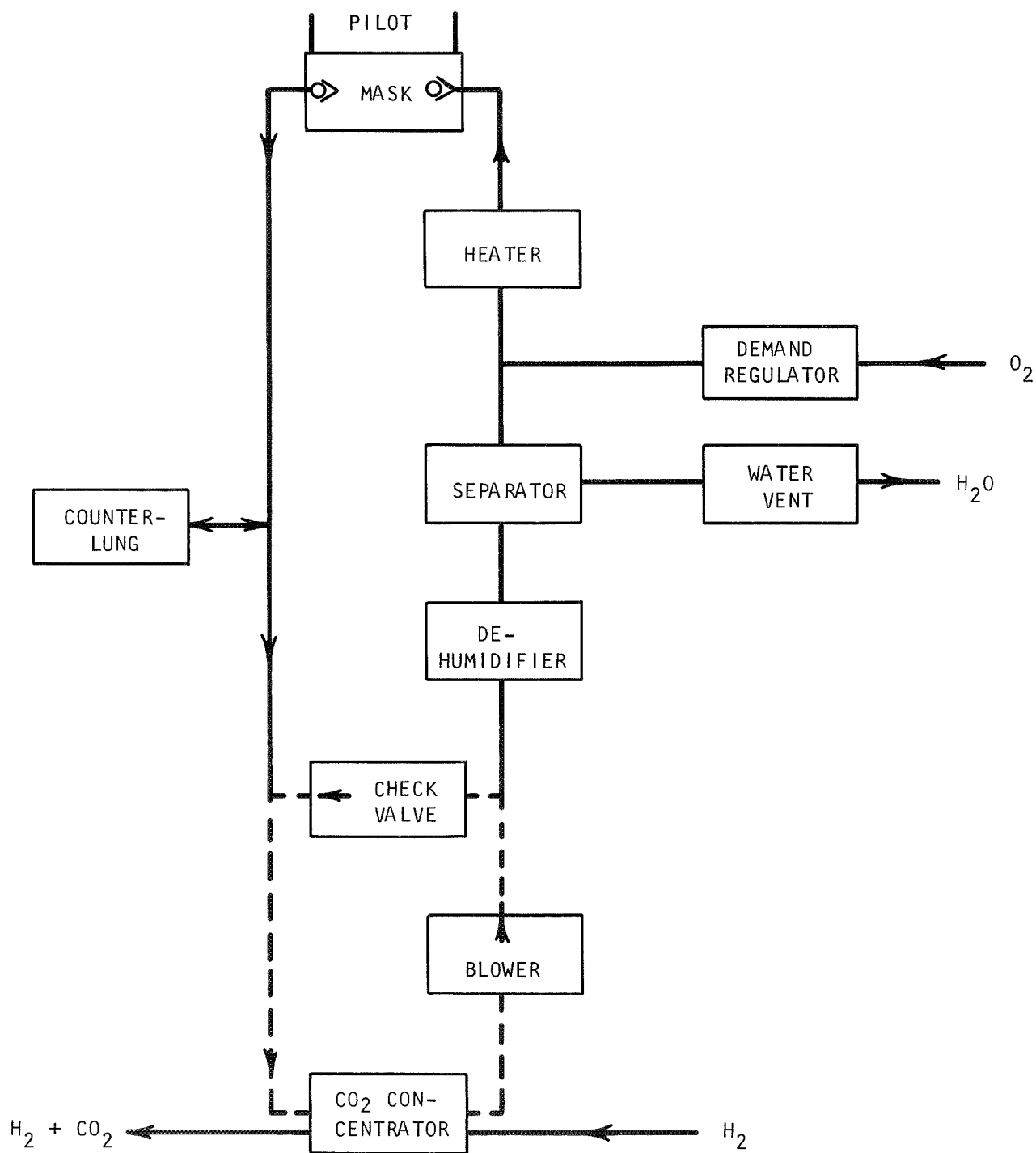


FIGURE 1 BREATHING LOOP SCHEMATIC

existing while breathing pure oxygen. The NAOS system will accomplish this by continually venting a small portion of the breathing gas.

The Water Electrolysis Subsystem (WES) is shown in Figure 2. The electrolysis module requires a pressure balancing system for safe, reliable operation. Oxygen is supplied to the breathing loop, as required, by the demand regulator. The control of the oxygen generation rate is accomplished by varying the electrical power to the electrolysis module. The module power control will adjust the electrical power to the electrolysis module to maintain a constant oxygen pressure as monitored by a pressure transducer.

A differential pressure regulator in the oxygen line is used to drop the pressure level so that the water feed will be maintained at 2 psi below the oxygen pressure. The hydrogen pressure is maintained between these pressures by a dome-loaded back pressure regulator. All pressures, therefore, are referenced to the oxygen pressure which in turn is controlled by power to the module. Figure 3 is a pictorial schematic of the complete NAOS system.

### System Analysis

A thermal analysis of the NAOS system was conducted to evaluate methods of maintaining a water balance in the carbon dioxide concentrator module and to determine the influence of component variables on the system performance. Cooling of the carbon dioxide concentrator by use of a separate heat exchanger in the circulating loop was not found to be practical due to the relatively low circulation flow compared to the sensible heat load. Also, it would be desirable to have nearly constant conditions of temperature and humidity in the circulating loop to avoid large temperature and water vapor pressure gradients in the carbon dioxide concentrator. External forced convection flow is therefore required.

The electrolysis module cooling by water evaporation would require either much higher operating temperatures or much lower pressures than presently specified. Operating the electrolysis module at a pressure level of 80 psia is desirable in that it allows a larger mass of oxygen to be stored in the cell cavities and oxygen manifolds which results in less sensitivity to pulsating flow demands of the breathing loop and would provide more reserve oxygen for emergencies. Operating the module at this high pressure and expanding down to the breathing loop pressure results in a low dew point in the hydrogen and oxygen feed lines. This, in turn, was found to result in very little interaction between the electrolysis module operation and other system components. The analysis showed that the electrolysis module operating temperature may be selected independent of the carbon dioxide concentrator module temperature. Variations in the electrolysis module temperature will have very small effects on the carbon dioxide concentrator module equilibrium electrolyte concentration. External forced convection cooling of the electrolysis module was selected and the control of the temperature could be fairly coarse.

Analysis of heat and mass transfer within the electrolysis module and carbon dioxide concentrator module showed that the gas conditions leaving these modules would be in equilibrium with the cells. That is, the gas exits at the cell temperature and with the same water vapor pressure as the electrolyte.

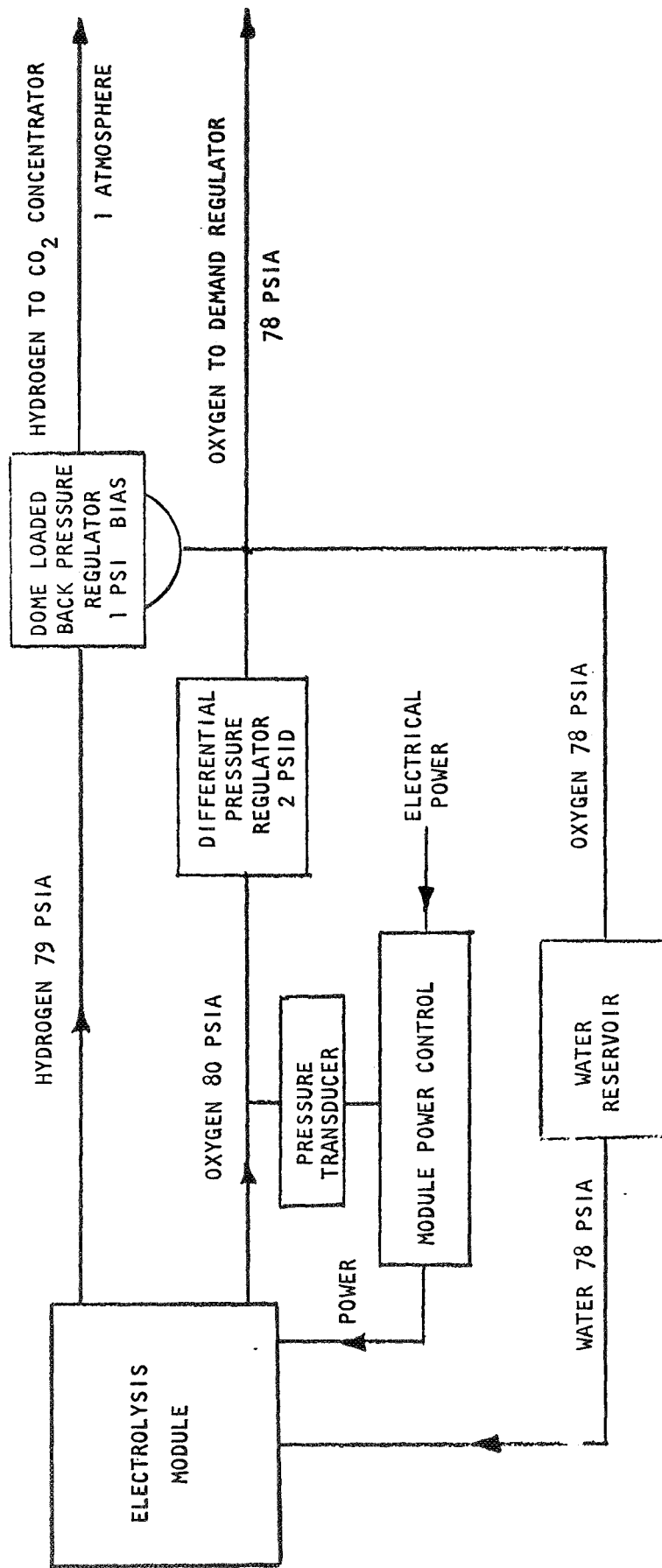


FIGURE 2 ELECTROLYSIS MODULE PRESSURE BALANCE AND CONTROL

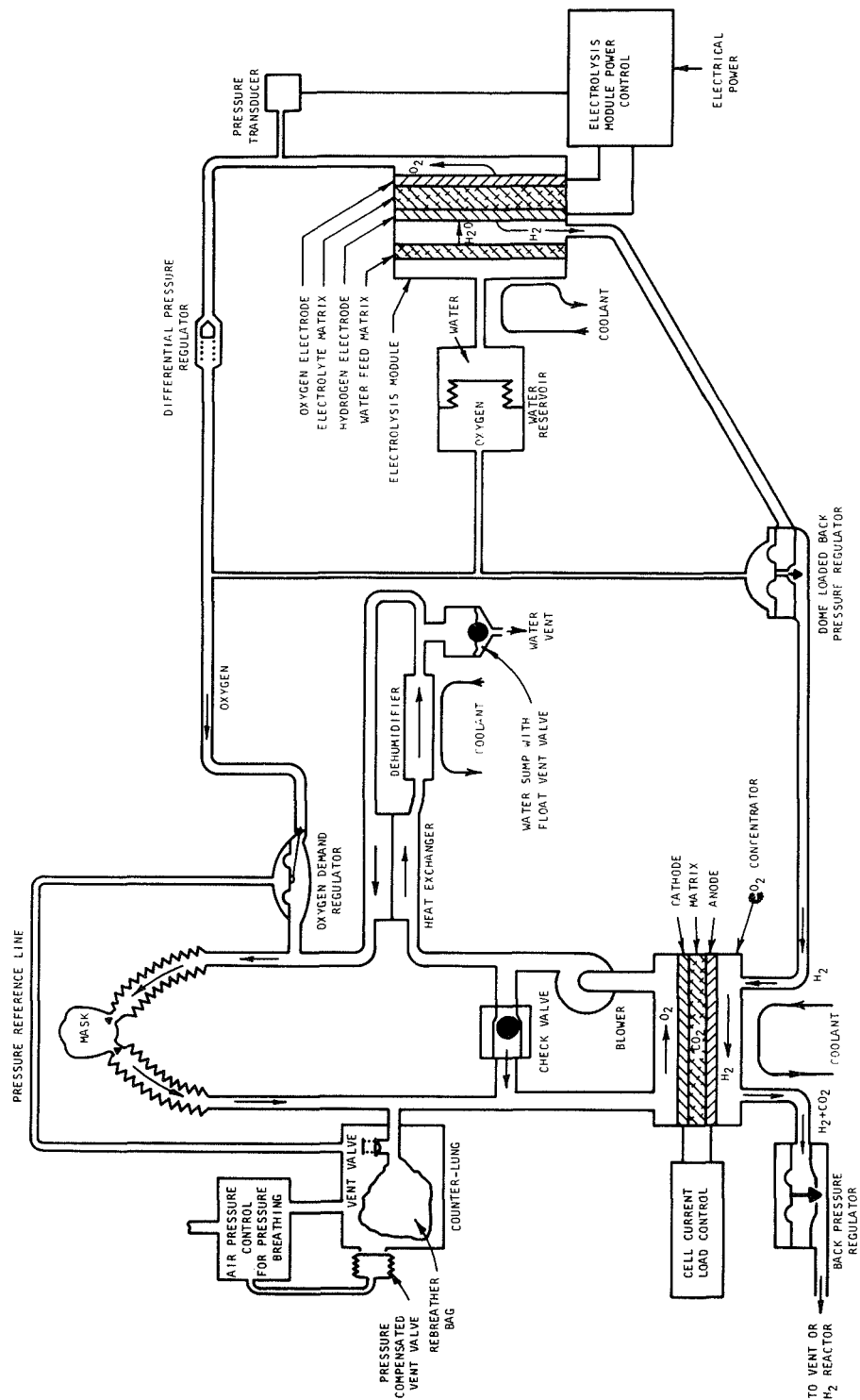


FIGURE 3 PICTORIAL SCHEMATIC, NASA AIRCREW OXYGEN SYSTEM

A very important consideration in the system is the maintenance of a relatively constant electrolyte concentration in the carbon dioxide concentrator. The electrolyte concentration can be controlled by maintaining a constant differential between the dew point temperature and the cell temperature in the concentrator module. This is because for a given electrolyte concentration the difference between the electrolyte temperature and the equilibrium dew point temperature is constant over a wide range of temperature.

### System Integration

After completing the initial design of the system to meet the design criteria previously discussed and evaluating the results of the system analyses, a complete system design was performed. This involved selecting and interconnecting components in the system to achieve the desired performance. Figure 4 shows the complete system design. The schematic shows the principal components as well as the related accessories such as the temperature control system, regulators, heat exchangers, instrumentation and warning system.

Heat rejection from the electrolysis module, carbon dioxide concentrator and dehumidifier will be accomplished by gas or liquid cooling systems aboard the aircraft. Temperatures will be controlled by regulating the coolant flow through these components. The gas regulators are required to maintain a pressure balance on the electrolysis cell, to provide pressure breathing at high cabin altitude, and to regulate pressure on the hydrogen side of the carbon dioxide concentrator. The heat exchangers in the breathing loop maintain comfortable oxygen conditions for the pilot. Instrumentation for system performance indication as well as warning alarms for safety are included.

### Component Specifications

A set of performance specifications were compiled for the principal components to be developed in the first phase program. These specifications are given in Table III. Some of the auxiliary components were specified after component parametric testing defined the requirements for the auxiliaries. The specifications in Table III were used as guides in the design of the system components.

### Projected Size and Weight

An estimate was made of the sizes and weights of the NAOS components for a fully-developed prototype. These are shown in Table IV. The estimates are based on refined cell construction methods and materials. Auxiliary component information reflects present technology, not necessarily in using existing components, but in manufacturing special purpose components. For example, a production unit would incorporate regulators with direct porting to other components rather than joining by using tubing and fittings. Components, therefore, require careful system integration considerations such that when combined into a system the optimum size and weight system is obtained. This is not the same as combining optimum components.

Also shown in Table IV is the present sizes and weights of some of the components. The large discrepancy between existing and projected values is due mainly to the "laboratory" design of these components for minimum cost and maximum safety.

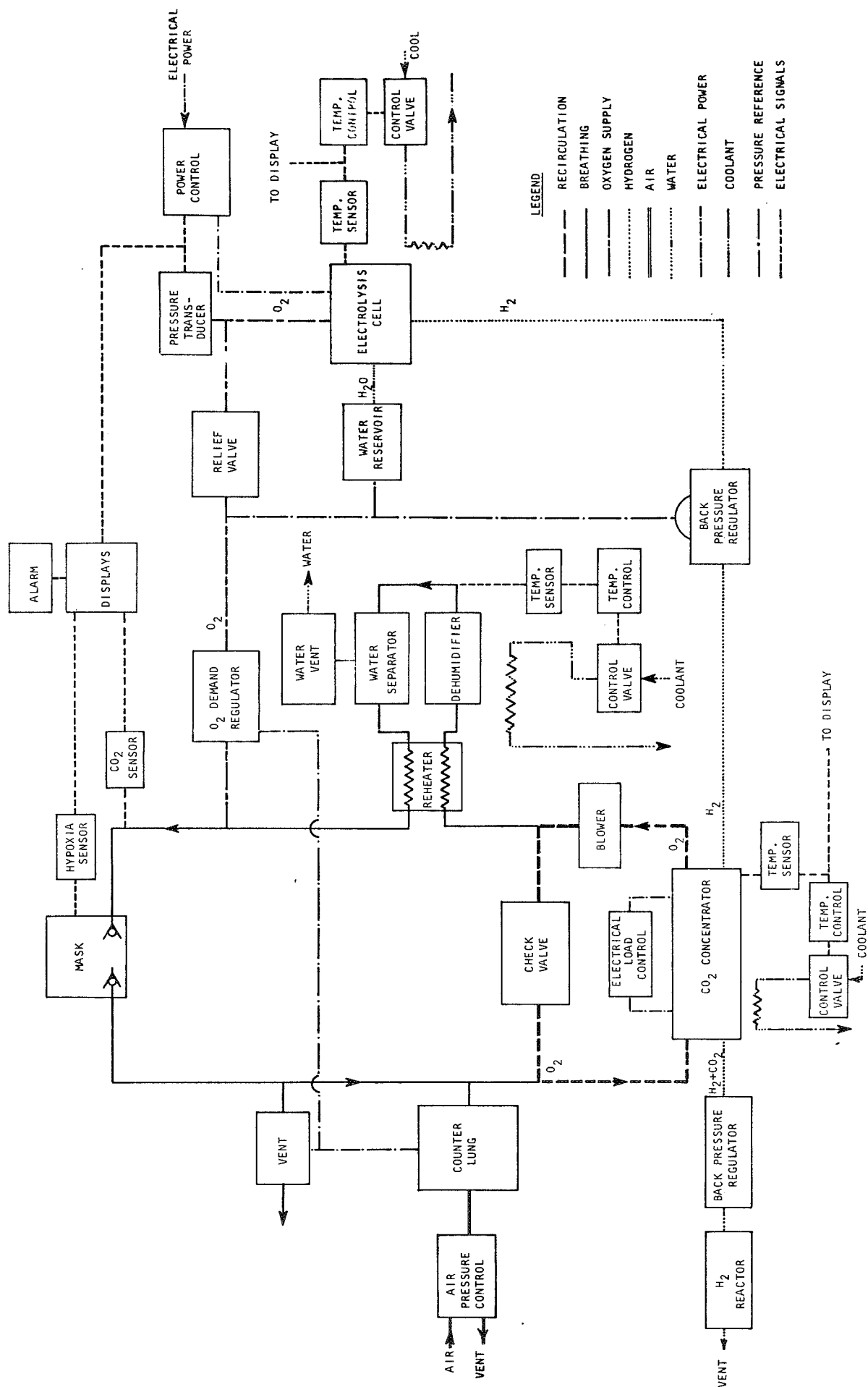


FIGURE 4 BLOCK DIAGRAM, NASA AIRCREW OXYGEN SYSTEM



TABLE III  
COMPONENT PERFORMANCE SPECIFICATIONS  
FIRST PHASE NAOS PROGRAM

Electrolysis Module Assembly

Oxygen Generation Rate:	0.15 lb/hr, nominal 0.20 lb/hr, maximum
Oxygen Supply Pressure:	77 ±3 psia
Hydrogen Pressure:	0 to 5 psi below O <sub>2</sub> pressure
Water Supply Pressure:	0 to 5 psi below H <sub>2</sub> pressure
Operating Duration:	10 hrs, continuous
Power Input:	0 to 30 amps, 20 volts maximum
Coolant:	Air
Cooling Load:	400 BTU/hr, maximum
Operating Temperature Range:	140-160°F

Electrolysis Module Water Reservoir

Useful Capacity:	1.9 lb water, minimum
Gas (O <sub>2</sub> ) Side Pressure:	72 ±8 psia
Gas (O <sub>2</sub> ) to Water Side Pressure Difference:	±0.5 psi

Carbon Dioxide Concentrator Module Assembly

CO <sub>2</sub> Removal Rate:	0.12 lb/hr, minimum
Operating Temperature Range (after start-up):	100 to 140°F
O <sub>2</sub> Side Total Pressure:	3 to 15 psia
H <sub>2</sub> Side Total Pressure:	3 to 15 psia
O <sub>2</sub> Consumption:	0.05 lb/hr, maximum
O <sub>2</sub> Side Circulating Flow:	2.0 CFM, minimum
O <sub>2</sub> Side Pressure Drop:	4 inches water at 3.5 CFM, 1 atm.
H <sub>2</sub> Side Inlet Flow:	0.018 lb/hr
CO <sub>2</sub> Partial Pressure at O <sub>2</sub> Exit:	7.6mm Hg, maximum
Operating Duration:	10 hrs, continuous
Coolant:	Air
Cooling Load:	300 BTU/hr, maximum

Counter Lung Assembly

Useful Volume:	1 liter
Differential Pressure, container above ambient:	1.0 psi, maximum
Vent Valve Cracking Pressure:	0.5 inches water

Blower

Pressure Flow:	6 inches water at 3.5 CFM
Electrical Power:	115 volts, 400 Hz, 250 milliamps

continued-

Table III - continued

Dehumidifier Assembly

Cooling Fluid:	Water or water-antifreeze solution
Oxygen Flow Rate:	0.5 CFM average, 2.0 CFM peak, flow vs time is a sine wave, positive flow only
Oxygen Inlet Temperature:	100°F to 140°F
Oxygen Outlet Temperature:	40°F to 60°F
Coolant Inlet Temperature:	40°F to 50°F
Oxygen Inlet Humidity:	Saturated
Coolant Flow Rate:	50 lb/hr, minimum

Electrolysis Module Power Control Unit

Voltage Input:	28 ±4 volts DC, 750 watts, maximum 115 volts, 400 Hz, 5 watts
Voltage Output to Module:	10 to 20 volts DC
Current Output to Module:	0 to 30 amps
Current Regulation:	±0.5 amps
Pressure Control Shut-Off:	80 psia
Pressure Control Proportional Band:	6 psi

CO<sub>2</sub> Concentrator Module Load

Load Current:	Manual set point 0 to 10 amps
Current Regulation:	±0.12 amps
Load Voltage:	2 to 12 volts DC
Control Power Input:	115 volts, 400 Hz, 5 watts

Counter Lung Air Pressure Control Regulator

Air Flow Rate:	0.5 CFM, average 2.0 CFM, peak
Safety Pressure:	1 to 2 inches water above ambient
Pressure Breathing:	MIL-R-19121D
Relief Pressure:	18 inches water
Air Inlet Pressure	50 psig, nominal

Oxygen Demand Regulator

Oxygen Inlet Pressure:	50 to 100 psia
Oxygen Outlet Pressure:	3 to 15 psia
Cracking Pressure:	0.5 inches water below dome loading pressure
Oxygen Flow Rate:	0 to 50 liters/min

TABLE IV  
PROJECTED PROTOTYPE SYSTEM SIZE AND WEIGHT

Components	Flight Size, Inches	Flight Weight, Pounds
Electrolysis Module	3x6x8	16
CO <sub>2</sub> Concentrator	8x7x2	10
Water Reservoir	4.1 dia x 5	3.5 filled
Counter-Lung	5x8.5x3.5	2
Blower	3 dia x 3	1.7
Dehumidifier	1x1x5	1
Reheater	1x1x3	.5
Electrolysis Module Power Control	5x6x4.5	2.5
Oxygen Demand Regulator	2 dia x 1	.2
Oxygen Differential Regulator	2 dia x 1	.3
Hydrogen Back Pressure Regulator	2 dia x 1.5	.4
CO <sub>2</sub> Concentrator Load Control	4x2.5x2	1.5
Hydrogen Vent Pressure Regulator	2 dia x 1	.3
Counter-Lung Pressure Control	3x4x2	.6
Electrolysis Module Coolant Valve	1 dia x 2	.2
CO <sub>2</sub> Concentrator Coolant Valve	1 dia x 2	.2
Dehumidifier Coolant Valve	1 dia x 2	.2
Water Vent Valve	1.5 dia x 2	.2
Circulating Loop Check Valve	1 dia x 0.5	.1
Electrolysis Module Pressure Transducer	1 dia x 1	.2
Control Electronics for Coolant Valves	3x3x4	1.5
Fittings, Ducting, Connectors		2.5
Total System Size	5x14x14	45.6

FIRST UNIT DEVELOPMENT SIZES AND WEIGHTS

Components	Present Size, Inches	Present Weight, Pounds
Electrolysis Module	4x4x8x11	51
CO <sub>2</sub> Concentrator	5x7x13	36
Water Reservoir	6 dia x 5.4	5 filled
Electrolysis Module Power Control	7.5x9x10	6.1
CO <sub>2</sub> Concentrator Load Control	5x6.3x8.5	3

For example, of the 51 pounds for the electrolysis cell, 20 pounds represents the steel endplates, where a high strength honeycomb is projected for the prototype. The prototype size and weight looks attractive. It is estimated that a packaged system will be near one-half of a cubic foot. The results of these size estimates were used to fabricate a mock-up of a system in prototype configuration.

### Engineering Mock-Up

The first step in constructing the model was to make rough component mock-ups to the projected sizes shown in Table IV. This was done rapidly and conveniently using styrofoam. The individual components were then assembled in many relative orientations to attempt to minimize the overall package envelope. Since neither a package configuration nor size limitation had been established, it was decided that a relatively flat, square package would be representative of an aircraft system which could, for example, be placed below an aviator's seat.

A significant effort was made to design the component interconnections of ducting, tubing and wiring for efficient use of space. Some of the component shapes were changed slightly for an improvement in package envelope. The counter-lung and electronics package were examples where modification of the shape did not change its performance but did aid the package design.

An assumption was made that liquid coolant would be used to cool the electrolysis module, carbon dioxide concentrator, power conversion and conditioning components and heat exchanger. This assumption allowed these components to be more compact since finned heat transfer surface was not required as with an air cooling method.

A rough styrofoam mock-up was used for package design. It is felt that such a design would have taken a much larger effort and time if it was attempted solely on a drawing board. Many options for component placement were examined rapidly by moving parts. The styrofoam mock-up took the place of a layout drawing of the package.

Once the package design was completed, the major components were fabricated of plastic. Several of the components such as regulators, valves and fittings were actual production pieces without internal parts. Figure 5 shows the completed prototype mock-up and Figure 6 shows the mock-up with a typical breathing mask and hoses. This mock-up represents the results of a detailed design effort in which all components are felt to be realistic in size and configuration. All electrical and plumbing connections are accounted for. Therefore, this mock-up represents an attainable configuration based on the projected efforts in the three phases of the NAOS development program.

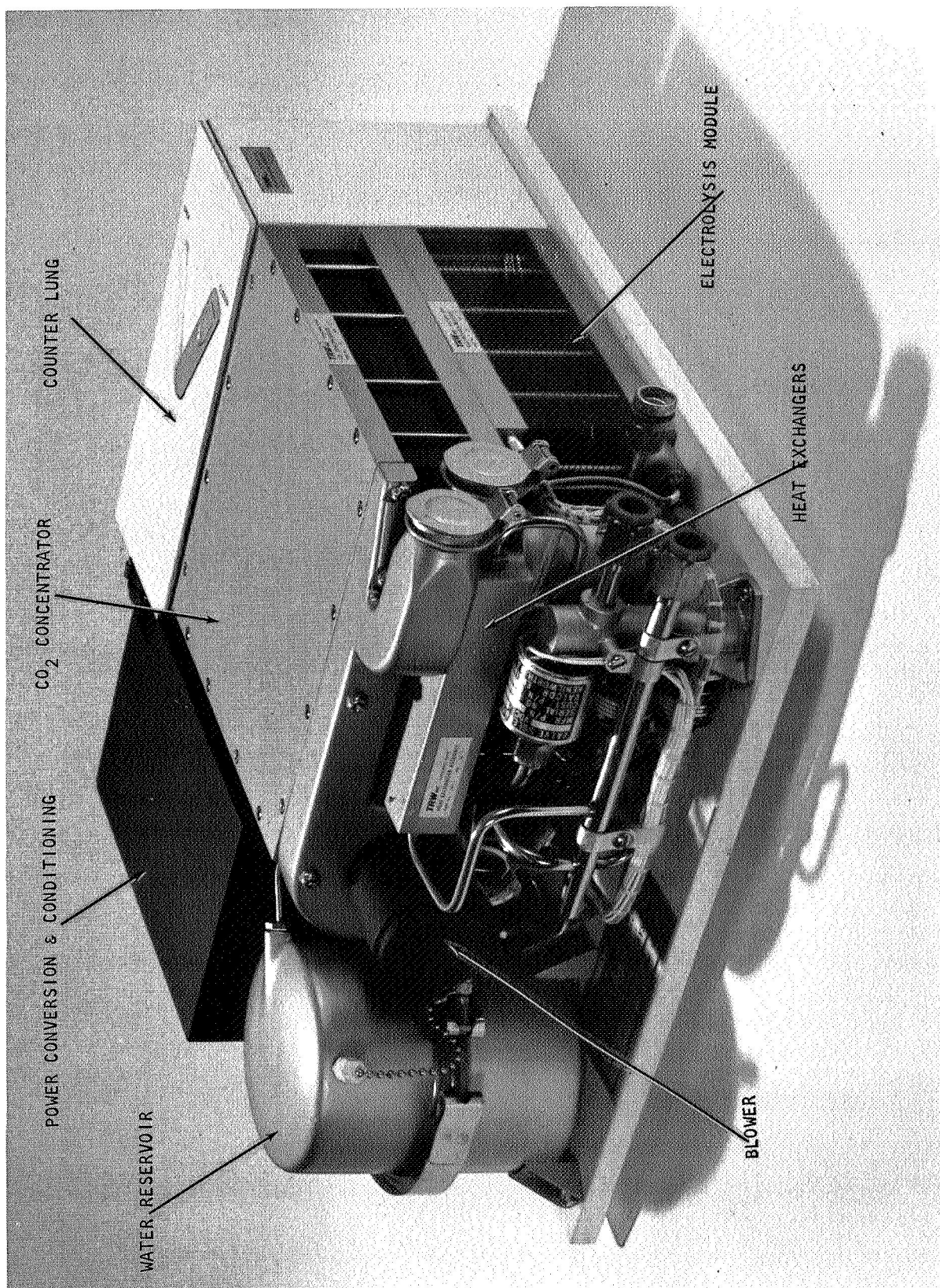


FIGURE 5 NAOS PROTOTYPE ENGINEERING MOCK-UP

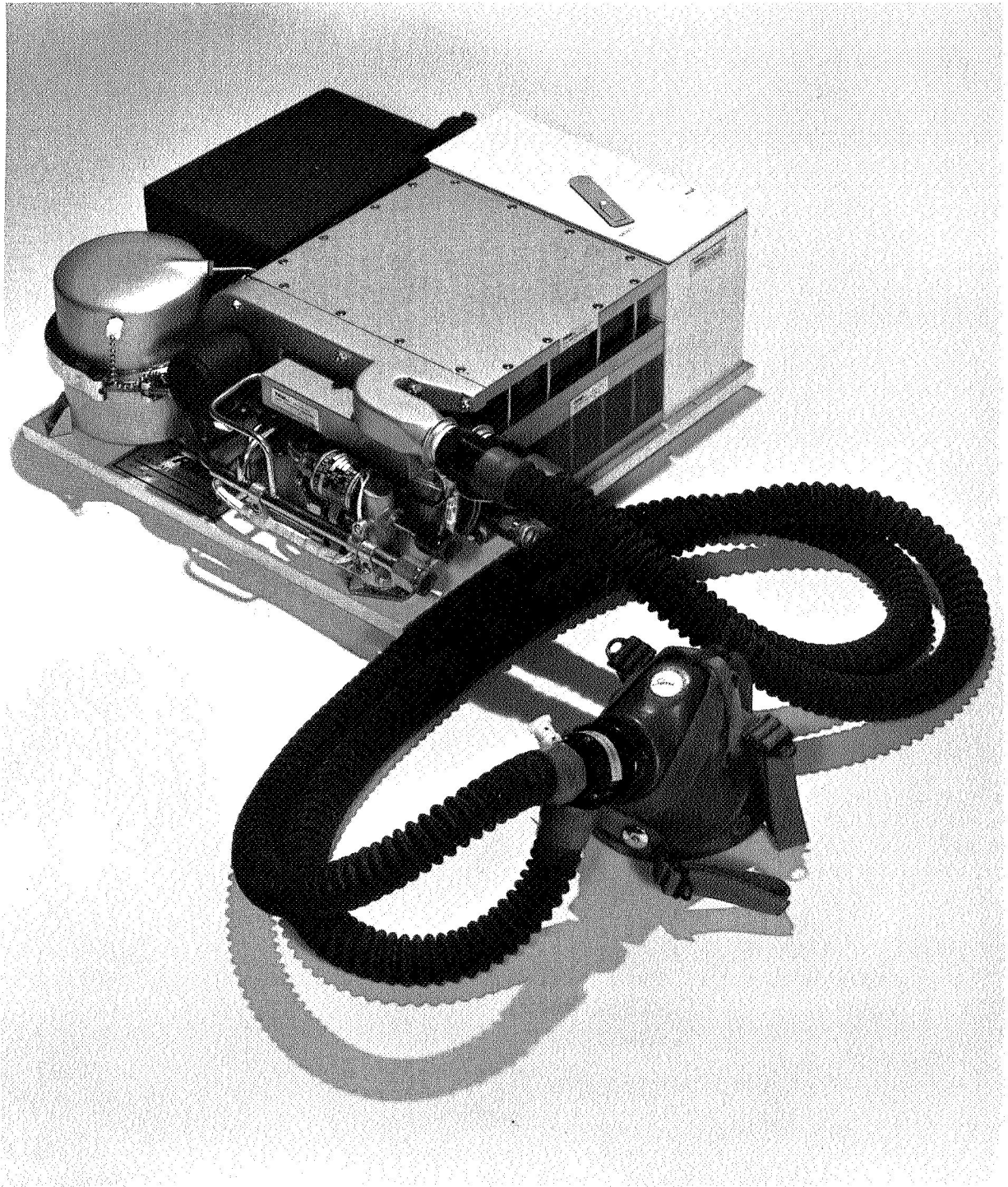


FIGURE 6 NAOS PROTOTYPE MOCK-UP WITH BREATHING MASK



## POWER CONDITIONING AND CONTROLS

This section describes the design and development efforts in the electrical power conditioning and controls subsystem. A major effort was in the area of the process rate controls of the two electrochemical components: the Water Electrolysis Module and the Carbon Dioxide Concentrator Module. In addition to this, a recirculating loop blower speed control and the electrochemical component temperature control systems were designed and fabricated.

### Electrolysis Module Constant Current Conditioner and Pressure Control

Design Guidelines. - The first step in the development of the power conditioning equipment was to set down specifications to be used as design goals. These specifications were determined from electrolysis module requirements, a knowledge of state-of-the-art power conditioner capabilities and typical aircraft power source availability. The specifications for the electrolysis module constant current power conditioner are shown in Table V. This table lists the design goals as well as the characteristics of the actual power conditioner as determined by laboratory tests on the breadboard. As can be seen, all goals were either met or exceeded.

Development. - The electrolysis module requires electrical power. In order to keep size and weight down and to keep efficiency high, a switching mode regulator was selected. To keep the filter components as small as possible a pulse width modulation (PWM) system operating at a frequency of 5K Hz was chosen. The basic current regulator system is shown in Figure 7a. The elements in the switch control will be discussed later.

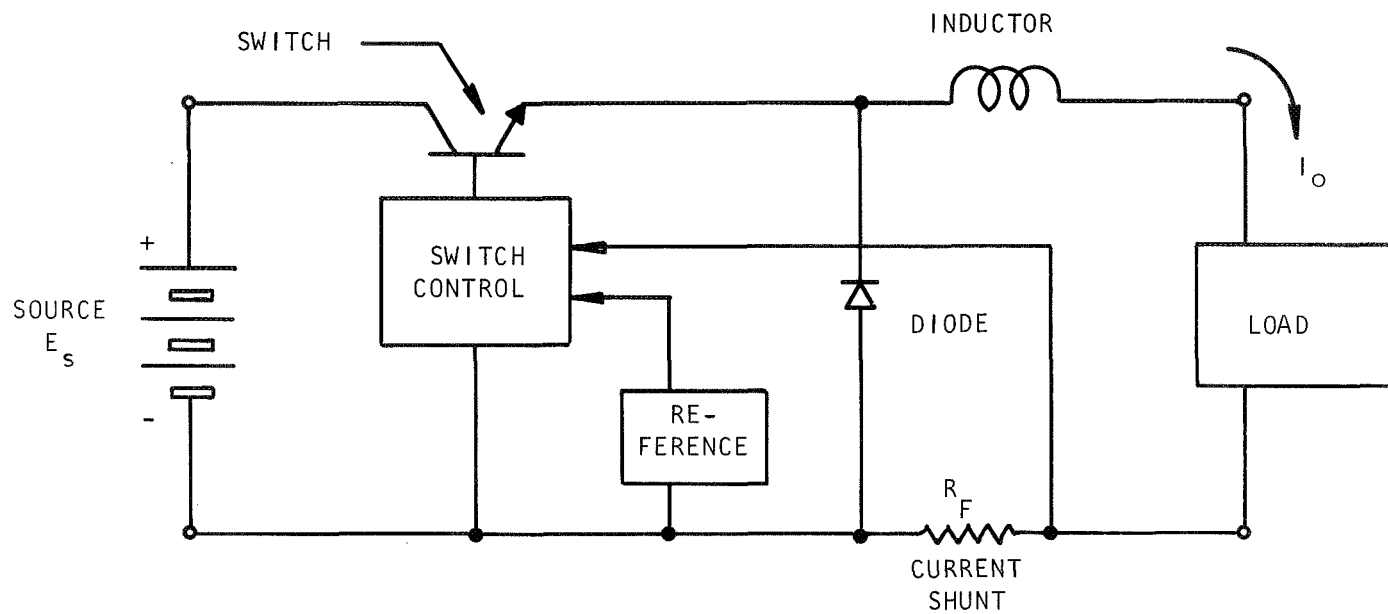
When the series switch transistor is on, full source voltage will be applied to the inductor, load and current shunt in series. Load current (and switch current) will increase exponentially at a rate determined by the ratio of the inductance to total series resistance. Just after the transistor switch is turned off, the inductor current will be the same as it was just before the transistor switch was turned off. The current will find a path that will allow this; the diode shown in Figure 7a provides this path. This continuity of current is caused by the fact that the energy stored in an inductance is proportional to the square of the current through it and the energy cannot be changed instantaneously. The energy in the inductor is fed to the load which causes the current to decrease exponentially. When the transistor switch is turned on again, it will pick up the load current flowing at that instant and the source will cause the current to increase again. To keep load current ripple and transistor switch peak current as low as possible, the choke has to be large enough to prevent large current changes during each part of this cycle.

By varying the amount of ON time in each cycle (or the duty cycle) the average load current can be varied. The current shunt is used to sense the load current and compare it with a reference in the switch control. If load current tries to increase for any reason, the switch control will cause the duty cycle to be reduced to lower the load current to the proper value and vice versa.

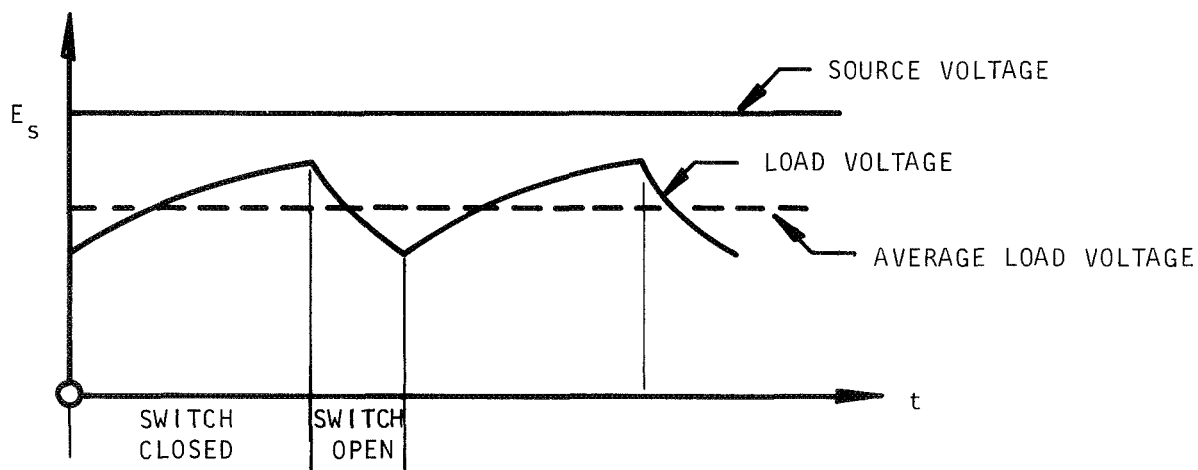
TABLE V  
ELECTROLYSIS CELL POWER CONDITIONER SPECIFICATIONS

		<u>Design Goals</u>	<u>Breadboard</u>	<u>Units</u>
I	Input	1) 28 $\pm$ 4	28 $\pm$ 4	Volts D.C.
		2) 115 $\pm$ 10	115 $\pm$ 10	Volts A.C.
		400 $\pm$ 40	50 to 440	Hertz
		50	7 max.	Watts
II	Output	0 to 20	0 to 20	Volts D.C.
		0 to 30	0 to 30	Amps D.C.
III	Efficiency	80 at full load	86 at full load	%
IV	Current Regulation			
	a. Line from 24 to 32 volts	3	0.04	%
	b. Load from 0 to 20 volts	3	0.02	%
V	Ripple	5	1	% rms





(a) BASIC CURRENT REGULATOR



(b) BASIC CURRENT REGULATOR WAVEFORMS WITH RESISTIVE LOAD

FIGURE 7 BASIC CURRENT REGULATOR AND WAVEFORMS

The waveforms shown in Figure 7b show (in an exaggerated form) what was described above. With a resistive load the load current and load voltage are the same form and are related by Ohms Law. In the actual design, the inductance will be sized to keep the load current ripple at a much lower value than shown to keep AC losses down and to keep transistor peak currents down.

Figure 8a is a more detailed functional diagram of the switch control block shown in Figure 7a. The comparator produces a high output voltage (which turns on the transistor switch) when the voltage from the amplifier is higher than the sawtooth signal and it produces a low output voltage (which turns off the transistor switch) when the sawtooth is larger than the amplifier signal. The amplifier looks at the reference (a negative DC voltage) and the voltage signal from the current shunt (a positive DC voltage) amplifies and inverts the difference between the magnitudes of the two voltages.

Thus if the reference signal is larger in magnitude than the current shunt signal, the amplifier will produce a positive output equal to its gain times the difference between the two inputs. The waveforms of Figure 8b show just such a situation and the resulting switch control signal.

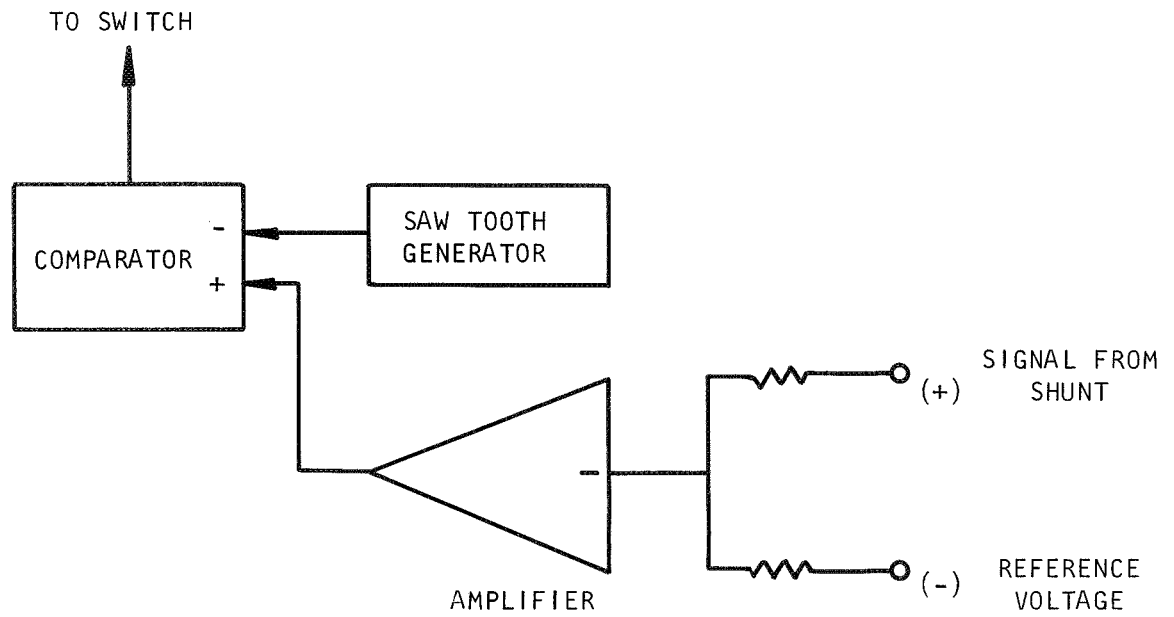
If the load current should increase for any reason such as load resistance decrease or an input voltage increase, the current shunt signal will increase. This will cause the amplifier output to drop. The comparator, and thus the switch, will then be turned off earlier in each cycle which will reduce load current as required (see Figure 8b). The gain of the amplifier is very high to DC signals approaching 50,000. This means that only very small load current changes will be required to compensate for large load resistance or input voltage changes.

The reference voltage mentioned in the previous paragraphs can be made a variable voltage and the load current will follow it. Thus a manual current control can be provided or as described later, a signal from an oxygen pressure transducer can be used to control the current conditioner to allow an oxygen pressure control system to be built.

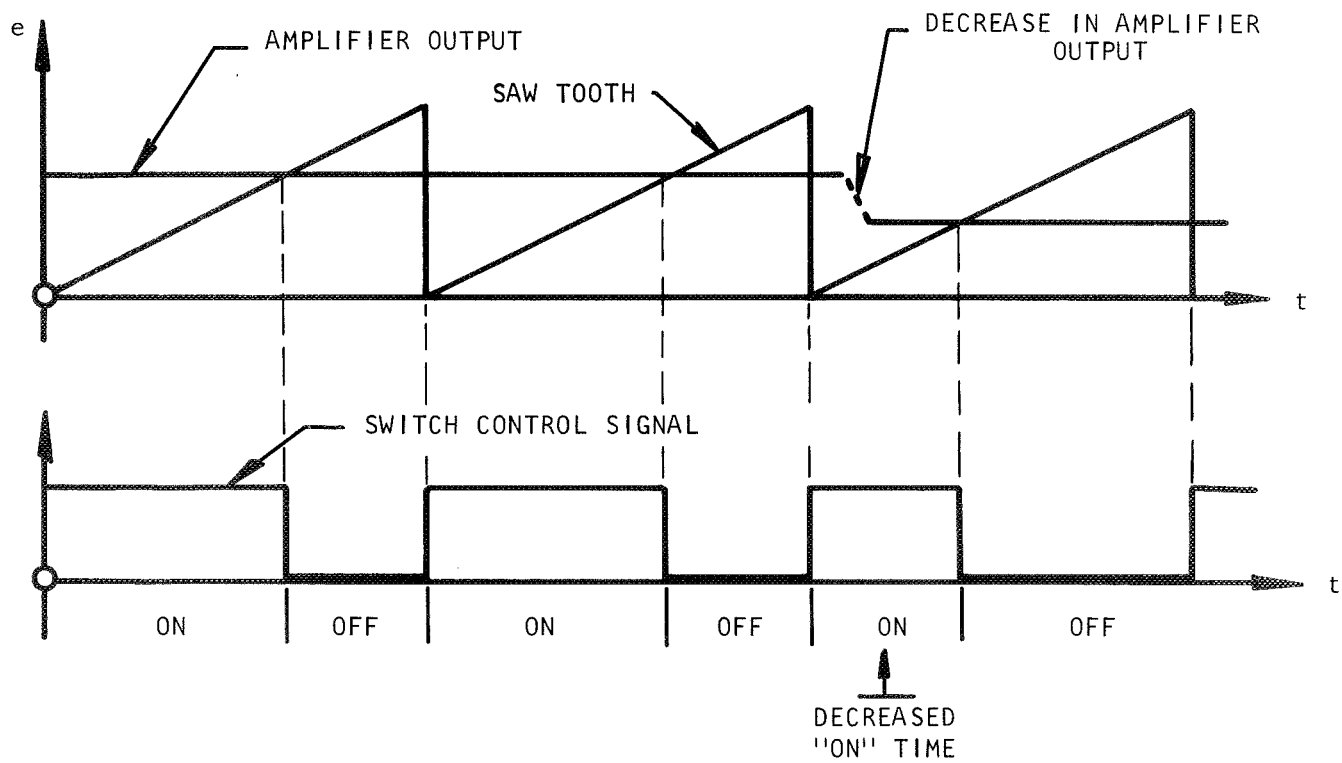
Figure 9 is a complete schematic of the breadboard conditioner as used in the Laboratory Breadboard System before the unit was rebuilt for increased capacity. Figure 10 shows the output characteristics of this conditioner at three input voltages and two load current set points.

In the initial stages of the development of the electrolysis stack power conditioner, several other schemes were examined. These all had one feature in common, the absence of an inductor in the load current path. It is virtually impossible to eliminate this element because load currents and current peaks become extremely high and uncontrollable. This imposes a severe stress on the series switch elements and requires a tremendous increase in their size, number and cost. Trying to limit this current by means of resistive elements is possible but reduces the conditioner's efficiency to a very low value and makes heat removal a big problem.

Examining the various approaches led to the conclusion that using an inductance for current limiting is the approach to take. Efforts to reduce the size of



(a) SWITCH CONTROL



(b) TYPICAL SWITCH CONTROL WAVEFORMS

FIGURE 8 SWITCH CONTROL AND WAVEFORMS

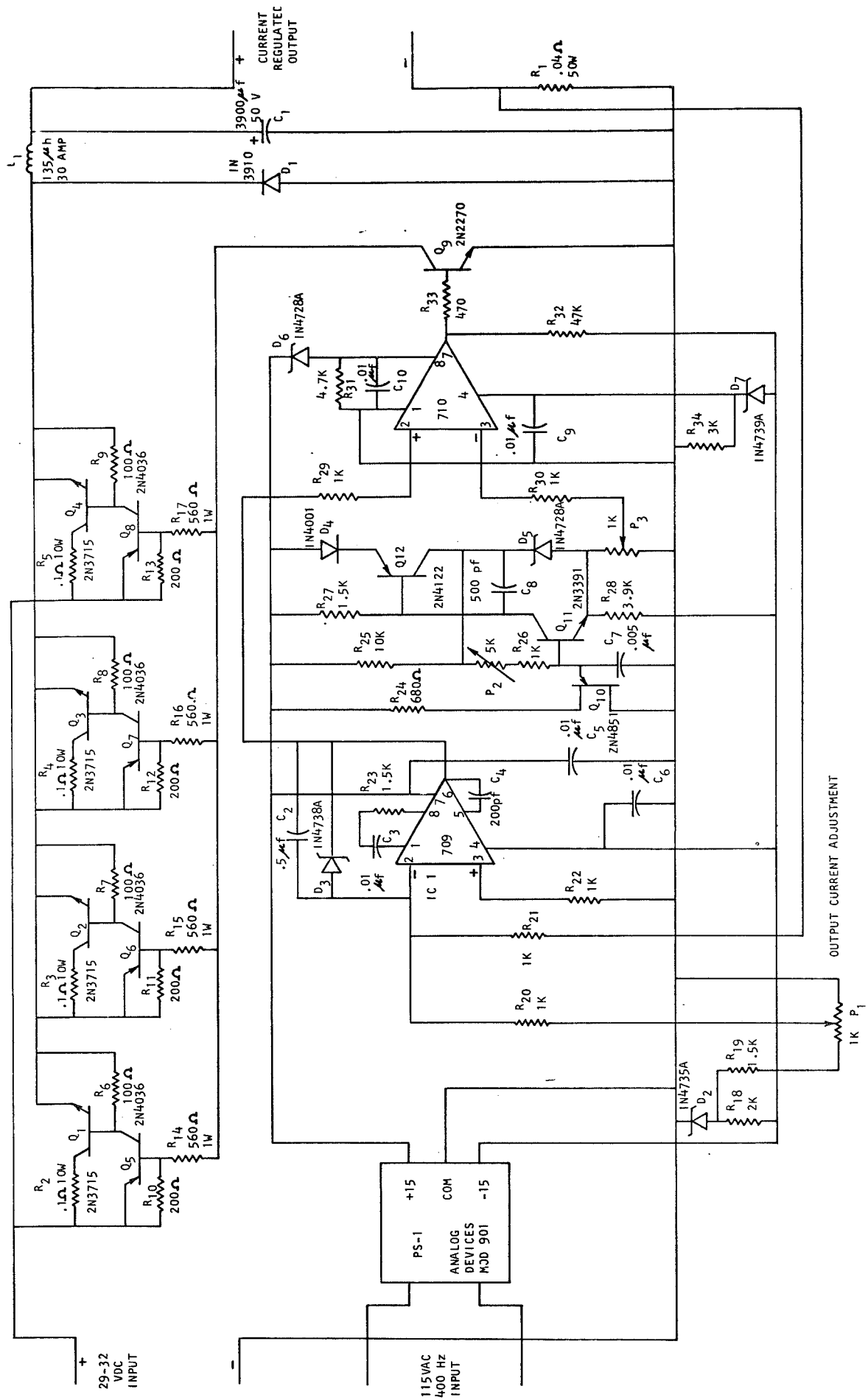


FIGURE 9 ELECTROLYSIS MODULE POWER CONDITIONING CURRENT REGULATOR SCHEMATIC

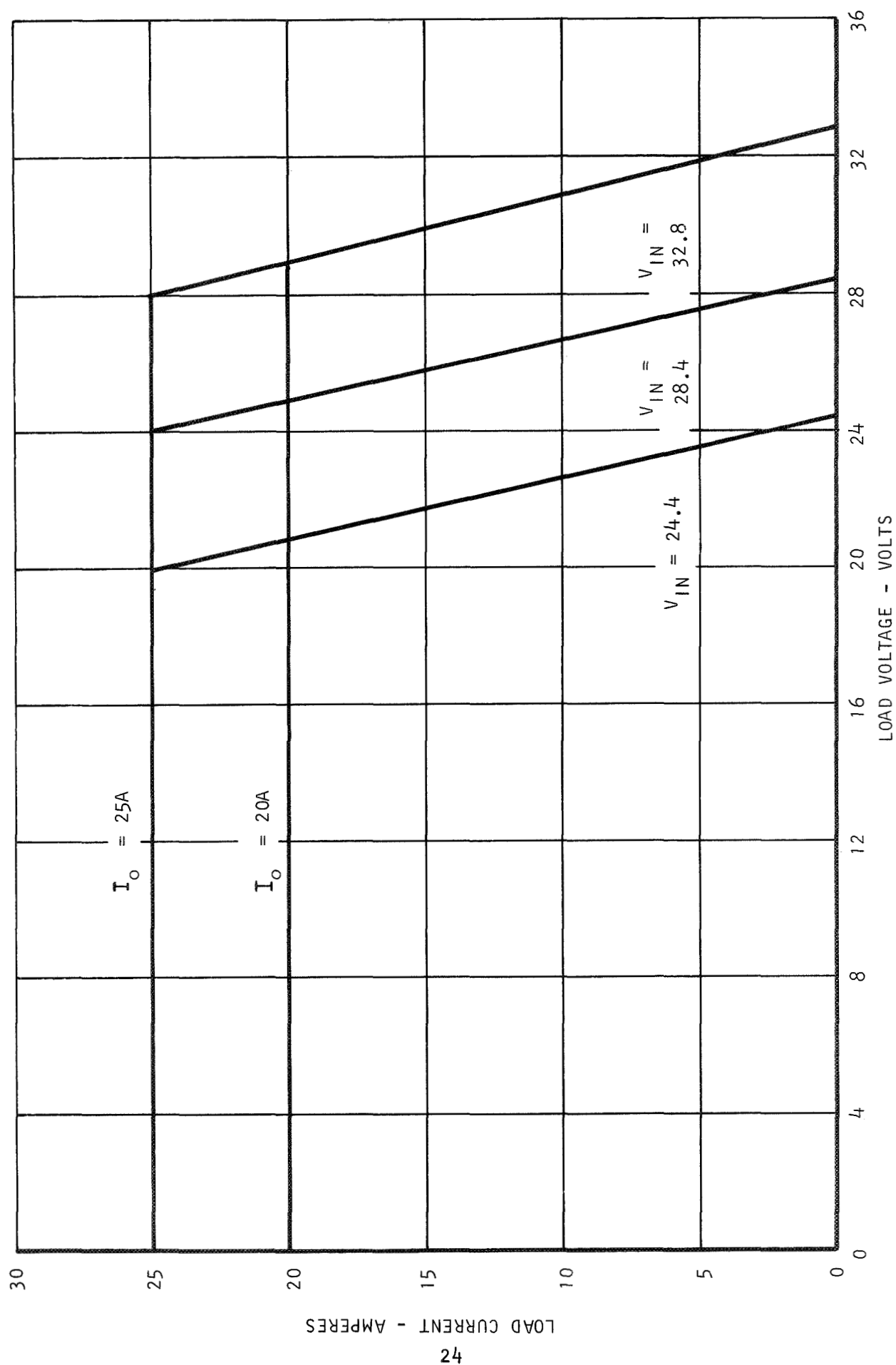


FIGURE 10 ELECTROLYSIS MODULE CURRENT REGULATOR CHARACTERISTICS

the inductance were fruitful in that the 17.6 pound, 5 1/2 inch by 4 1/2 inch by 5 inch inductor used in a previous similarly rated constant current conditioner was reduced to a 1.43 pound, 2 1/2 inch long by 3 1/2 inch diameter unit with an improvement in regulation as a further benefit.

The electrolysis module power conditioner as described above was modified to include a pressure regulated current control and a current limiter. Also, a modification was made to increase the efficiency of the unit. The basic power supply, however, remained unchanged. The changes made the power conditioner more compatible with the requirements of the test stand and the flight modified unit. Figure 11 is a block diagram of the complete power conditioner and pressure control subsystem. The current sensing shunt was changed to a lower resistance. The resistance was changed from 0.04 ohm to 0.005 ohm to cut the power lost in this resistor from 25 to 3.2 watts. This change increased the overall efficiency from 81 to 86 percent. An amplifier was used to bring the 0.005 ohm resistor output voltage up to the value previously obtained from the 0.04 ohm resistor as shown in Figure 11.

The electrolysis module power conditioner as previously described was an adjustable constant current conditioner. This means that any change in stack characteristics and/or source voltage would not change stack current but stack current could be set by adjusting a potentiometer. The system requirements call for the use of a pressure control on the oxygen output from the electrolysis module. To implement this, a pressure transducer was connected to an amplifier (A3 in Figure 11) whose output was then used in place of the manual current set point control. The amplifier output was phased such that an increasing pressure caused the conditioner output current to decrease. Thus, when the pressure transducer was installed in the oxygen output line of the module, a closed loop pressure control system resulted.

At start up or during periods of excess oxygen drain, the pressure will be low and module current could become excessive. To prevent this a current limiting circuit, shown in Figure 11, was included. When the output current reaches a value such that the voltage output of A1 becomes equal to the reference connected to the input of A2, the output of A2 changes to limit the output current.

Figure 12 is a photograph of the breadboard of the electrolysis module power conditioner. The electrolysis module power conditioner was designed for versatility and ease of varying operating parameters. This was done to make the integration of the conditioner into the complete system as simple as possible. Closed loop stability, gain and set points are all adjustable (generally independently).

Figure 13 shows the current versus pressure characteristic curve for the power conditioner. The magnitude of the limited current can be changed by varying the reference input to A2, the slope of current versus pressure in the control region can be varied by changing the gain of A3, and the pressure at the design operating point can be varied by changing the pressure reference voltage into A3.

From 0 to 74 psia, the current limiter holds the module current to a constant 28 amperes. When the pressure increases above 74 psia, the pressure transducer

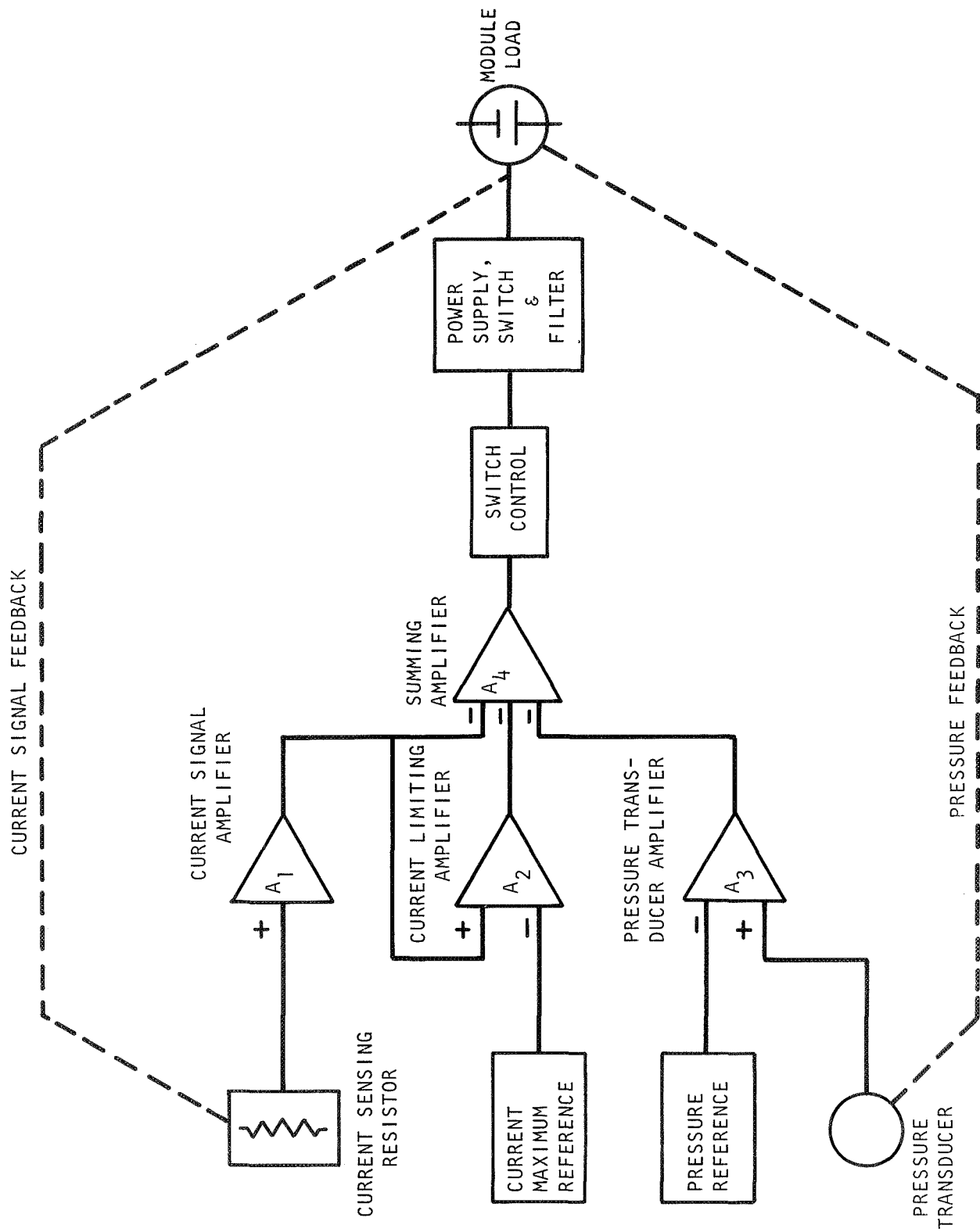


FIGURE 11 BLOCK DIAGRAM - ELECTROLYSIS MODULE PRESSURE CONTROL SUBSYSTEM

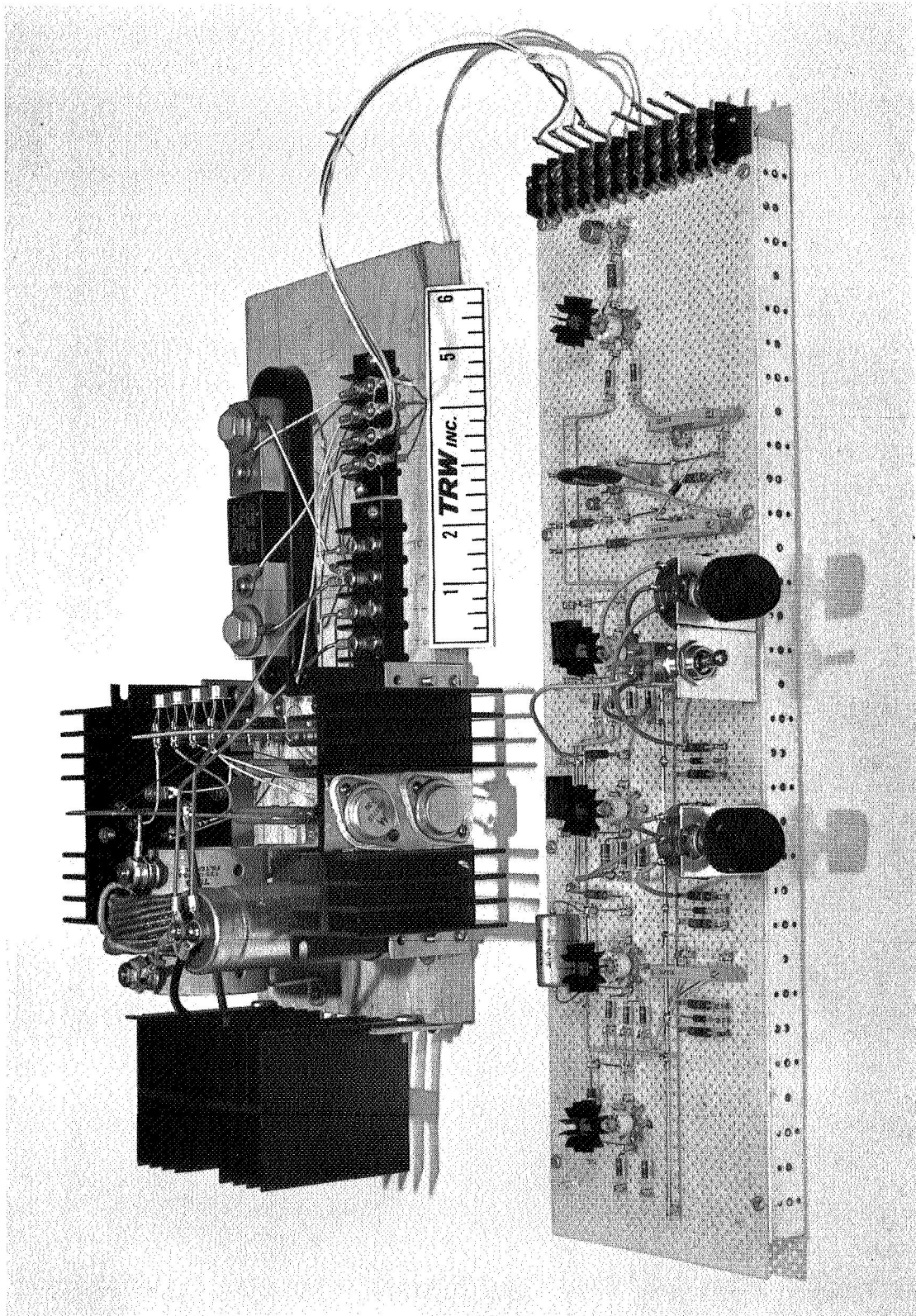


FIGURE 12 ELECTROLYSIS MODULE PRESSURE CONTROL BREADBOARD



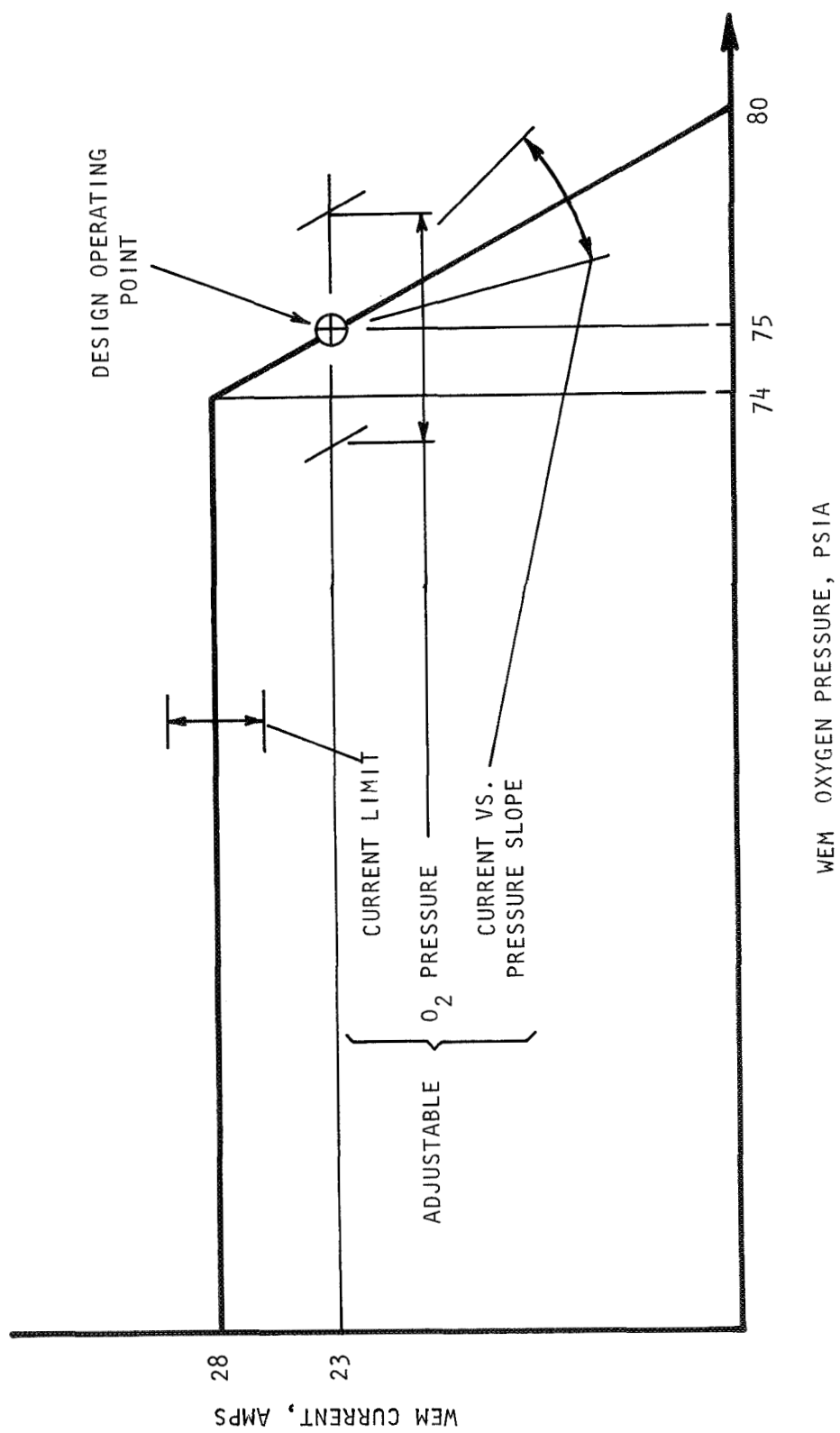


FIGURE 13 WES CONTROLLER CHARACTERISTICS

controls the current causing it to decrease as pressure increases until at 80 psia the current is reduced to zero.

Assuming the design oxygen flow rate of 0.15 lb/hr is being taken from the electrolysis module, the oxygen pressure will increase until the current is reduced to 23 amps. As shown in Figure 13, this will occur at about 75 psia. If the rate of oxygen being taken from the module is reduced, the pressure will increase until the current drops to the value necessary to supply the oxygen being used. The control system will adjust the module current to the value required by the module to supply the oxygen being delivered. Module oxygen pressure will vary as required to accomplish this.

The breadboard electrolysis module current control (see Figure 12) was installed in the laboratory breadboard system and operated for over 2,000 hours in both the manual (constant current with manual current setting) and the automatic pressure control modes. There were no failures in the equipment nor were there any detectable design deficiencies. Its performance in the automatic pressure control mode was excellent.

#### CO<sub>2</sub> Concentrator Load

Design Guidelines. - Figure 14 shows the carbon dioxide concentrator load voltage versus current characteristic which was used as a design guide. The breadboard developed for this load will operate at any point within the solid line enclosed area in Figure 14, which covers the majority of the module operating area and includes the expected operating point of the module.

In addition, a current regulation of three percent and power consumption less than 10 watts from the 400 Hz aircraft power system were selected as design goals. The breadboard current regulation was measured to be two-tenths percent and the 400 Hz power consumption was 7 watts.

Development. - The schematic of Figure 15 shows the original carbon dioxide load circuit. It consisted of a series transistor, Q1, which is controlled by transistors Q2 and Q3. The operational amplifier compares the load current (as measured by the two 0.1 ohm resistors, R1 and R2 in parallel) with a reference voltage on the wiper of control P1. The difference between these two signals is used to control the series power transistor such that the load current is maintained constant at the value set by control P1. The amplifier gain is so large that only very small load current changes are produced by large input voltage changes.

Most of the power from the carbon dioxide concentrator is dissipated by the power transistor, Q1. If an automatic control of some other concentrator dependent variable is desired, it can be accomplished by substituting a signal proportional to this variable for the load current control potentiometer, P1.

Figure 16 shows the breadboard of the carbon dioxide concentrator load as installed in the LBS. The breadboard load has been operated for over 600 hours with no failures. It performed as expected during this period.

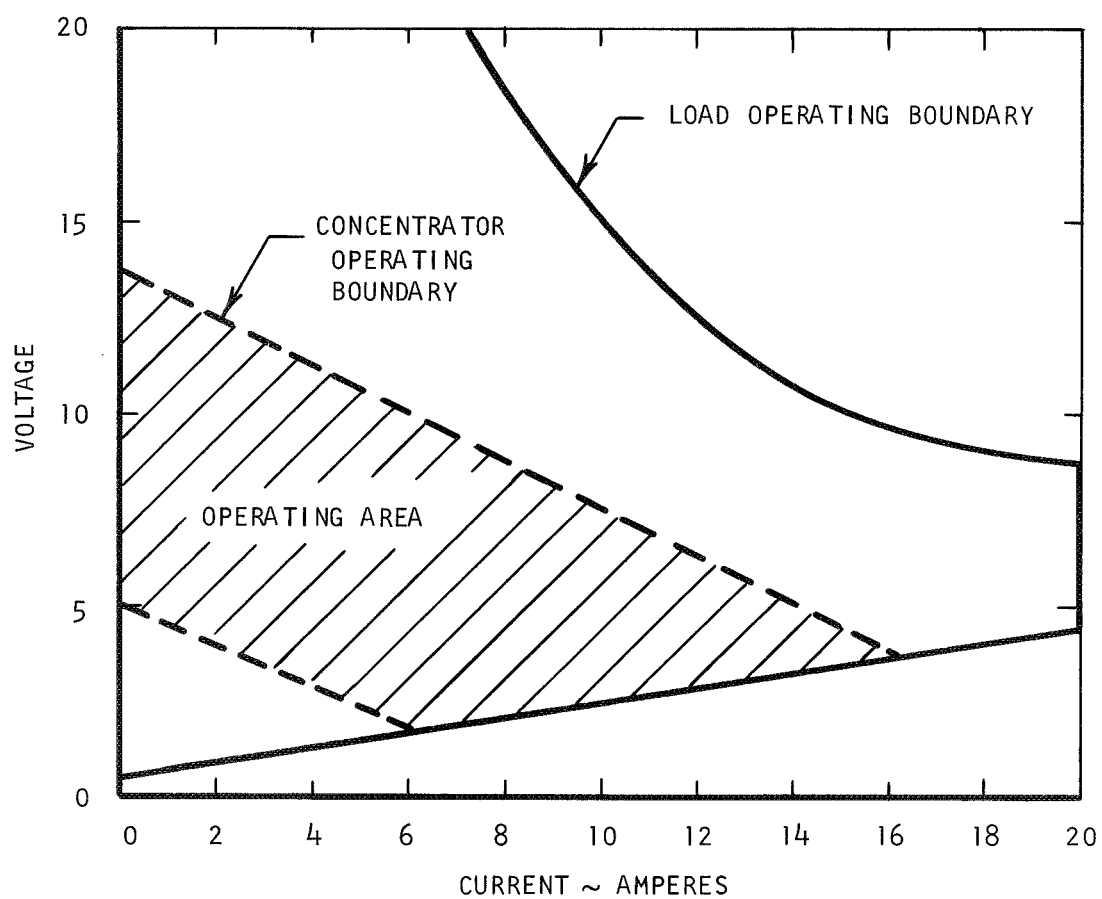


FIGURE 14 CO<sub>2</sub> CONCENTRATOR CONSTANT CURRENT LOAD OPERATING AREA



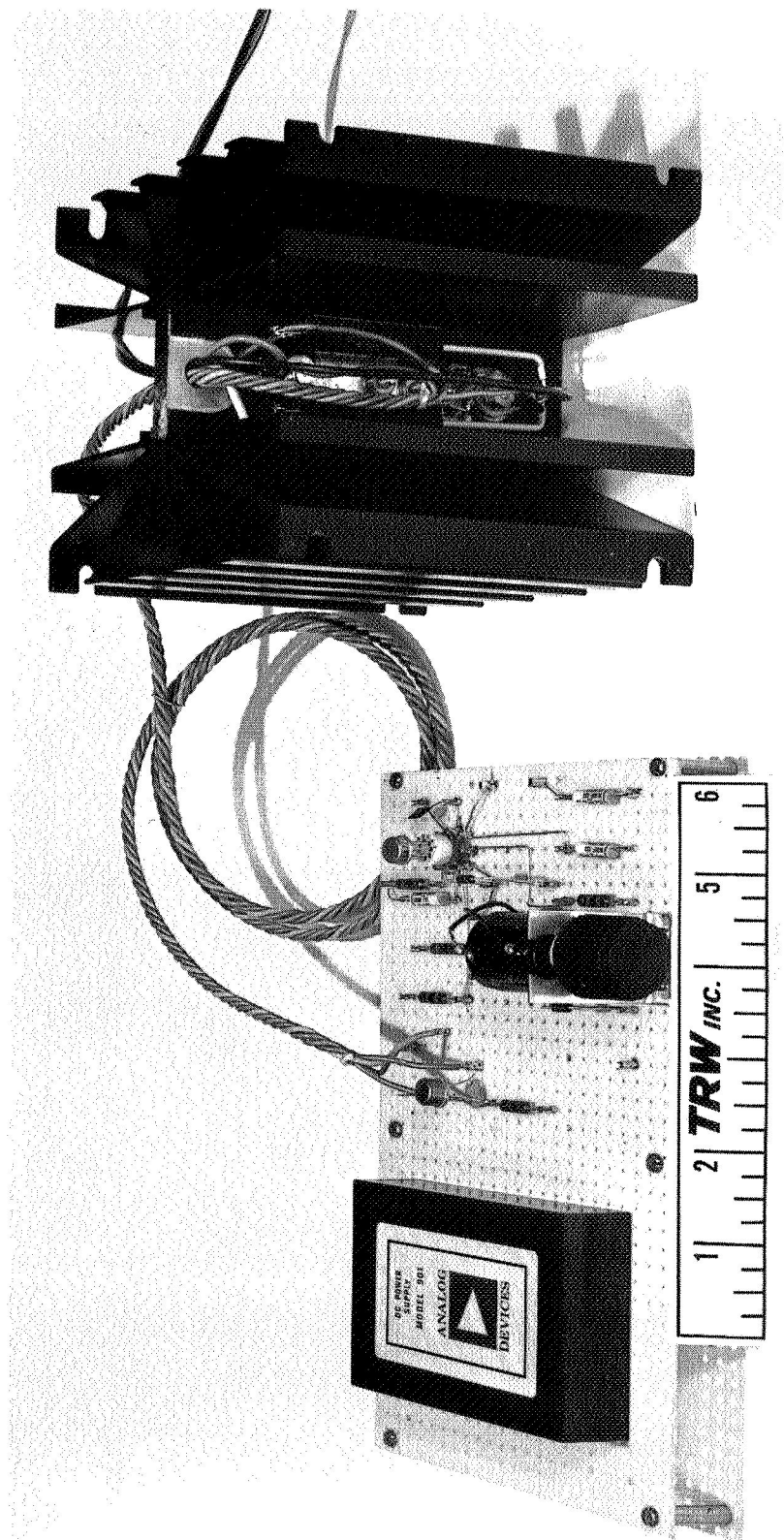


FIGURE 16 CO<sub>2</sub> CONCENTRATOR CONSTANT CURRENT LOAD BREADBOARD

## Blower Control

The blower used in the rebreather loop has an induction motor that operates from the 115V 400 Hz AC power available on modern aircraft. This type of motor, with a fan load, works well with a phase control.

The phase control shown in Figure 17 controls the voltage applied to the blower. The flow rate set point, P1, controls the capacitor, C1, charging rate. When the voltage across C1 reaches the firing voltage of the three layer diode, (D1) C1 is discharged into the diode which in turn fires the TRIAC, turning it on for a half cycle. When the resistance of P1 is low, C1 charges quickly and turns on the TRIAC early in the half cycle. This allows the fan to operate at high speed. Conversely, when the resistance of P1 is high, the TRIAC fires late in each half cycle, allowing little power to reach the fan and causing low fan speeds.

Two meters monitor voltages and currents associated with the blower. These parameters give good indication of closed loop flow rate and pressure drop.

## Thermal Controls

Internal power losses will cause the electrolysis module and the carbon dioxide concentrator module to heat up. If no cooling were provided the modules would heat up to temperatures greater than the desired operating temperatures. Fins are provided on the module to bring the internal heat to the outside where blowers are used to remove the heat and thereby cool the modules. A thermistor is located in a strategic spot in each module to measure its temperature. This thermistor is connected to an electronic control which turns the module cooling blower on and off to maintain a set temperature as shown in Figure 18. When the module temperature goes below the set temperature, the blower is turned off. The internal dissipation causes the module temperature to increase. When the temperature exceeds the set temperature, the control turns the blower on to cool the module.

A block diagram of the temperature control is shown in Figure 19. The thermistor is a temperature-sensitive resistor with a large, non-linear, negative temperature coefficient as shown by the curve in Figure 19. The thermistor amplifier, linearizes the thermistor output signal, amplifies it and converts it to a low impedance level for driving readouts and the comparator. The comparator circuit compares the signal from the thermistor amplifier with the signal from the set point which is a function of the desired operating temperature. When the thermistor temperature is higher than the desired temperature, the thermistor amplifier output signal is greater than the signal from the set point. The comparator output will turn the AC switch on and send 400 Hz power to the blower. When the thermistor temperature drops enough to make the thermistor amplifier output drop below the signal from the set point, the comparator will cause the AC switch to turn off, which turns the blower off.

The control, with the components used in its breadboard, will turn power on and off with a difference in temperature of less than  $0.1^{\circ}\text{C}$ . The breadboard has been tested on the bench using a simulated system. It was temperature cycled

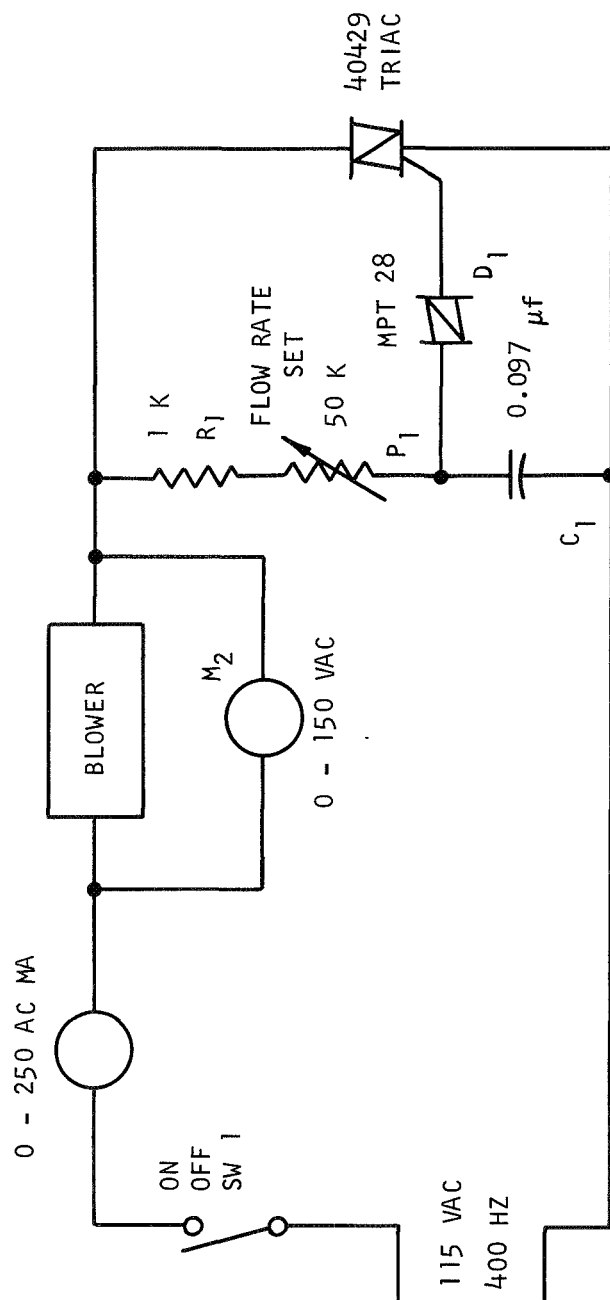


FIGURE 17 REBREATHER LOOP BLOWER CONTROL SCHEMATIC

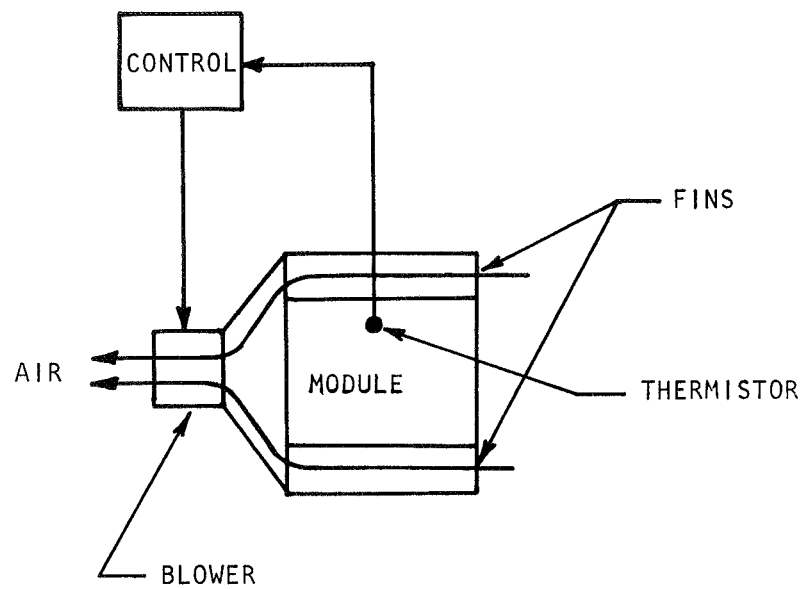


FIGURE 18 ELECTROLYSIS MODULE AND CO<sub>2</sub> CONCENTRATOR  
MODULE TEMPERATURE CONTROL SYSTEMS



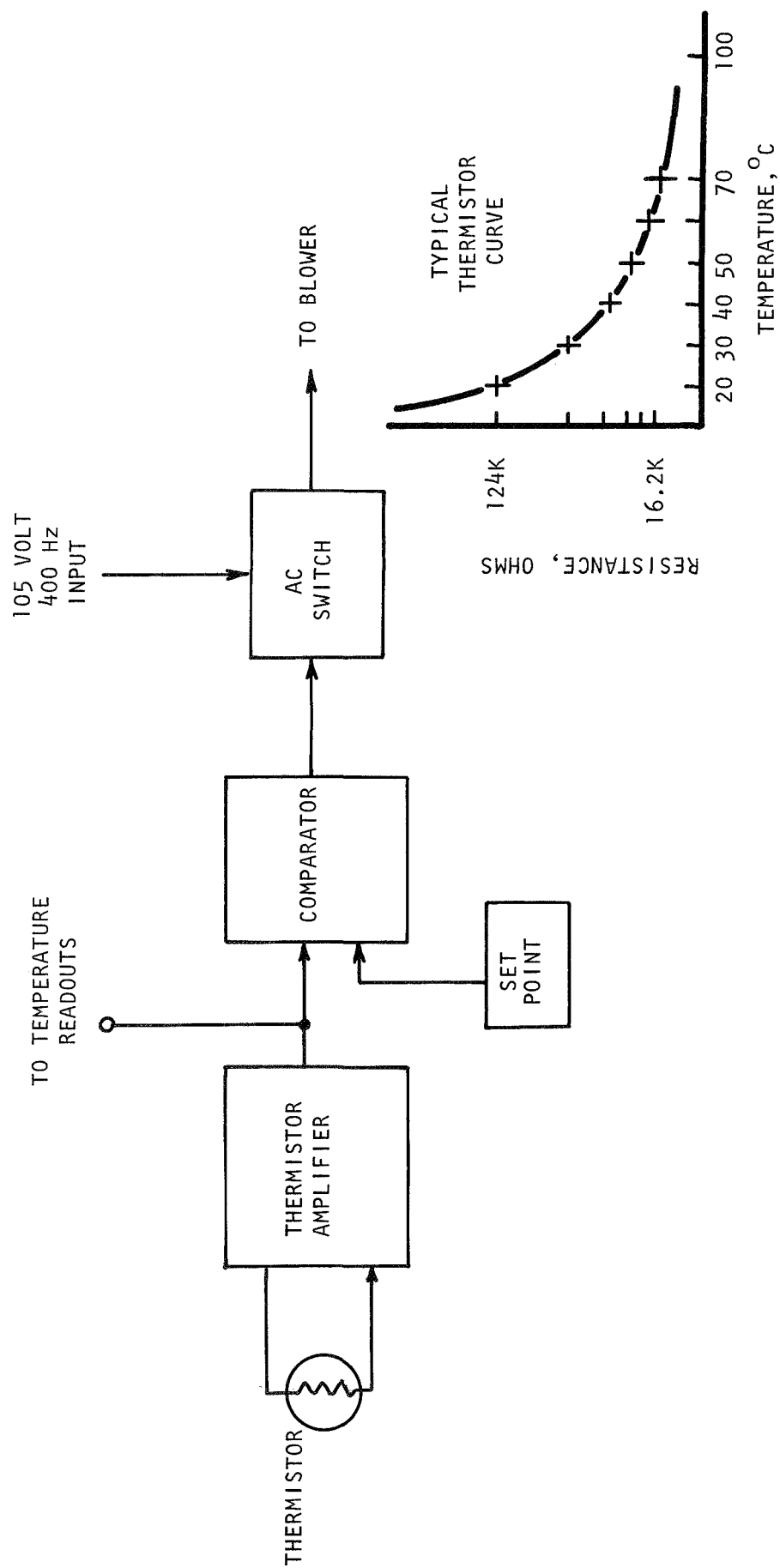


FIGURE 19 CDCM TEMPERATURE CONTROL BLOCK DIAGRAM

from room temperature up to 65°C and found to be quite stable. This breadboard was then installed into the laboratory breadboard test rig to control the carbon dioxide concentrator module temperature. The control maintains the concentrator temperature at the desired value and has performed well in the breadboard system.

## SYSTEM ACCESSORIES

System accessories are defined as those items not specifically in the major electrochemical component subsystems, specifically, the electrolysis module subsystem or the carbon dioxide concentrator module subsystem. The electrical power conditioning and controls subsystems were described in a previous section. The accessory components, therefore, are the remaining components in the rebreather loop such as the counter-lung and pressure control, the recirculating loop blower, and the heat exchangers. The hydrogen elimination device is also discussed in this section. Most of these accessory components have been mentioned or discussed in the breadboard tests. The accessories are required to meet performance but are not necessarily flight size or weight. Therefore, standard off-the-shelf components were employed wherever possible for use in the laboratory breadboard system.

### Rebreather Loop Components

The rebreather loop accessory components include the counter-lung, counter-lung pressure control, recirculating blower and heat exchangers.

Counter-Lung/Pressure Control. - The counter-lung functions as a volumetric gas reservoir to accommodate the variation in the breathing loop gas volume as the aviator inhales and exhales. If not included in the closed loop, large variations in pressure would result making breathing difficult. The counter-lung is a flexible bag within a rigid container. The inside of the bag is connected to the breathing loop. The outside of the bag is pressurized with air, normally about one inch of water pressure above cabin pressure. This prevents cabin air from leaking into the system. At altitudes requiring pressure breathing, the counter-lung is pressurized to the standard pressure breathing schedule starting at 38,000 feet cabin altitude.

The air pressure, which is equal to the rebreather loop pressure because of the flexible bag, is controlled by the counter-lung pressure control regulator. Figure 20 shows the arrangement of the counter-lung and pressure control. The pressure control regulator, using an available aircraft air source, supplies gas pressure outside the bag during the inhalation portion of the breathing cycle. An aneroid control following the required pressure schedule controls the pressure. An exhalation pressure compensated valve allows venting of air from the pressurized container during exhalation to maintain desired operating pressure.

Note the physical location of the demand regulator is such that its diaphragm is referenced to the rebreather bag container pressure which, in turn, is already altitude compensated. This method of diaphragm reference serves to eliminate the need for an additional altitude aneroid.

The nitrogen vent is necessary to continuously remove, from the rebreather loop, that nitrogen which is eliminated from the body cavities, liquids, and tissues and that initially in the loop. The method originally considered was to adjust the rebreather bag size to each aviator such that the bag would be slightly smaller than the aviator's tidal volume. (This method was later

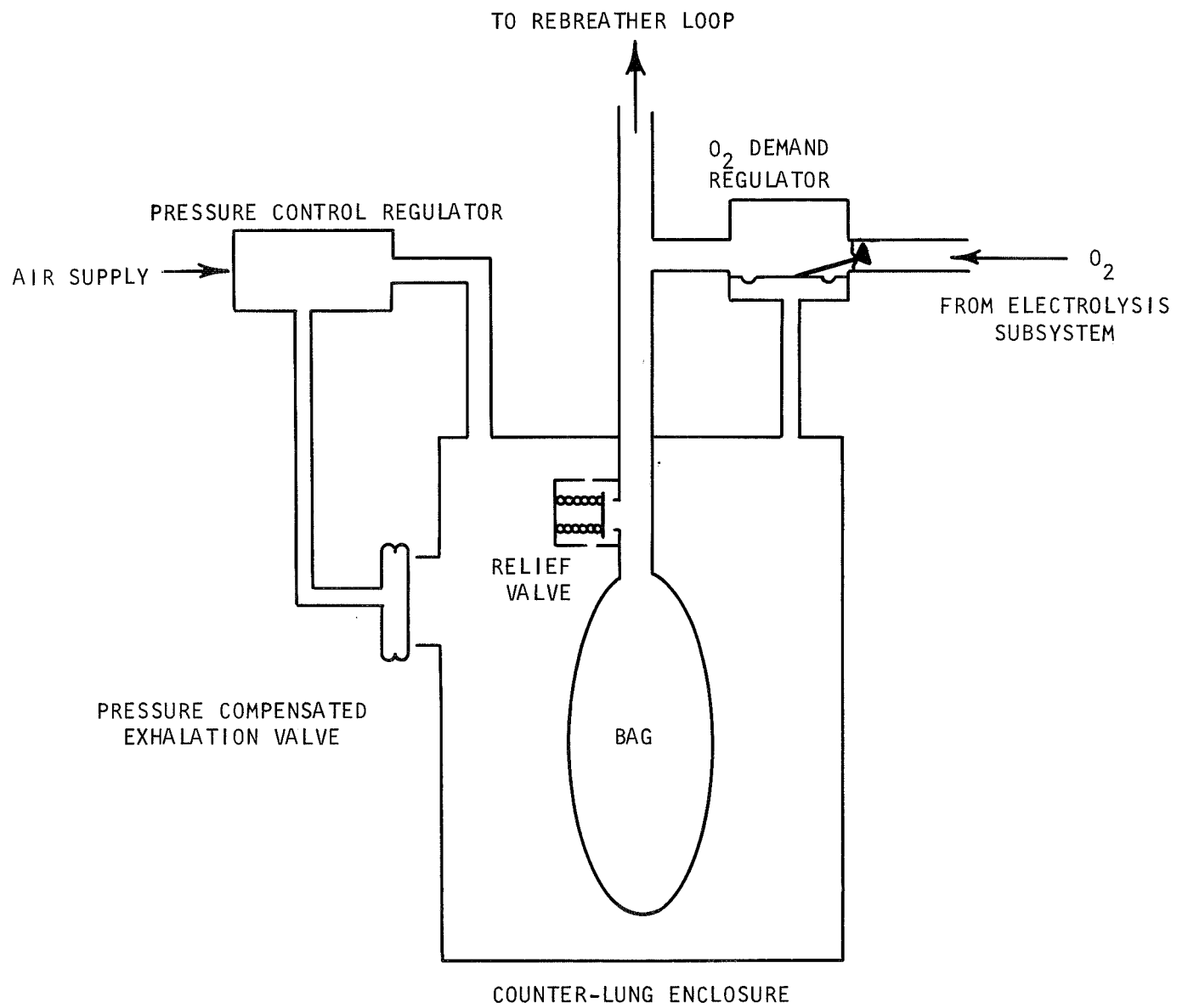


FIGURE 20 COUNTER-LUNG AND PRESSURE CONTROL

abandoned in favor of a continuous purge of the rebreather loop.) During each exhalation the relief valve will open when the bag becomes fully inflated and the loop pressure begins to rise above the air pressure in the container. Conversely, on inhalation, when the rebreather bag becomes fully collapsed and the loop pressure begins to fall below the air pressure, the demand regulator will open to supply oxygen from the electrolysis module.

Aircraft oxygen system component manufacturers were asked to recommend existing components or those easily modified to meet NAOS requirements. This includes the counter-lung, pressure control and some of the auxiliary regulators and valves.

Quotations for many of the accessory components were received from both Aro-Buffalo Corp. and Scott Aviation. Many items were lightweight, miniature components applicable to the final system. For the present program, however, only those items which could not be purchased as standard were further investigated. These items included the counter-lung, counter-lung pressure control, and oxygen demand regulator.

A counter-lung was fabricated from transparent plastic to allow observation of the rebreather bag during operation. A standard one liter medical breathing bag was used. The counter-lung design was based on ease of fabrication and to allow rapid assembly and disassembly for modifications during testing. No attempt was made to optimize the size or shape for packaging. Figure 21 shows the counter-lung with the air pressure control regulator and the vent valve mounted. These latter two items were purchased from Aro-Buffalo Corp.

A counter-lung air pressure control and an oxygen demand regulator were purchased from both Scott Aviation and Aro-Buffalo Corp. This allowed two slightly different designs to be tested and evaluated and provided a back-up available in case of a failure. The Scott design has the counter-lung pressure control regulator and the oxygen demand regulator in the same housing. Compressed air is metered into the counter-lung box at a rate slightly higher than the maximum instantaneous breathing flow rate. The air exits from the box through the pressure compensated vent valve which is controlled to give the required pressure breathing schedule at high altitudes. The oxygen demand regulator is referenced to the vent valve pressure which is essentially rebreather loop pressure.

The Aro-Buffalo system regulates compressed air into the rebreather box to maintain the pressure breathing schedule. Air is vented from the box through a pressure balanced vent valve as the box pressure rises on exhalation. The oxygen demand regulator is a separate component which has a pressure reference line to the rebreather box. Both of the above systems admit oxygen through the demand regulator only when the rebreather loop pressure falls below the counter-lung air pressure which can only occur when the rebreather bag is fully collapsed.

The counter-lung pressure control regulators and oxygen demand regulators were tested individually and in a complete rebreather loop with the counter-lung operated by a breathing simulator. This allowed these components to be tested under cyclic flow conditions which could not be duplicated otherwise. The

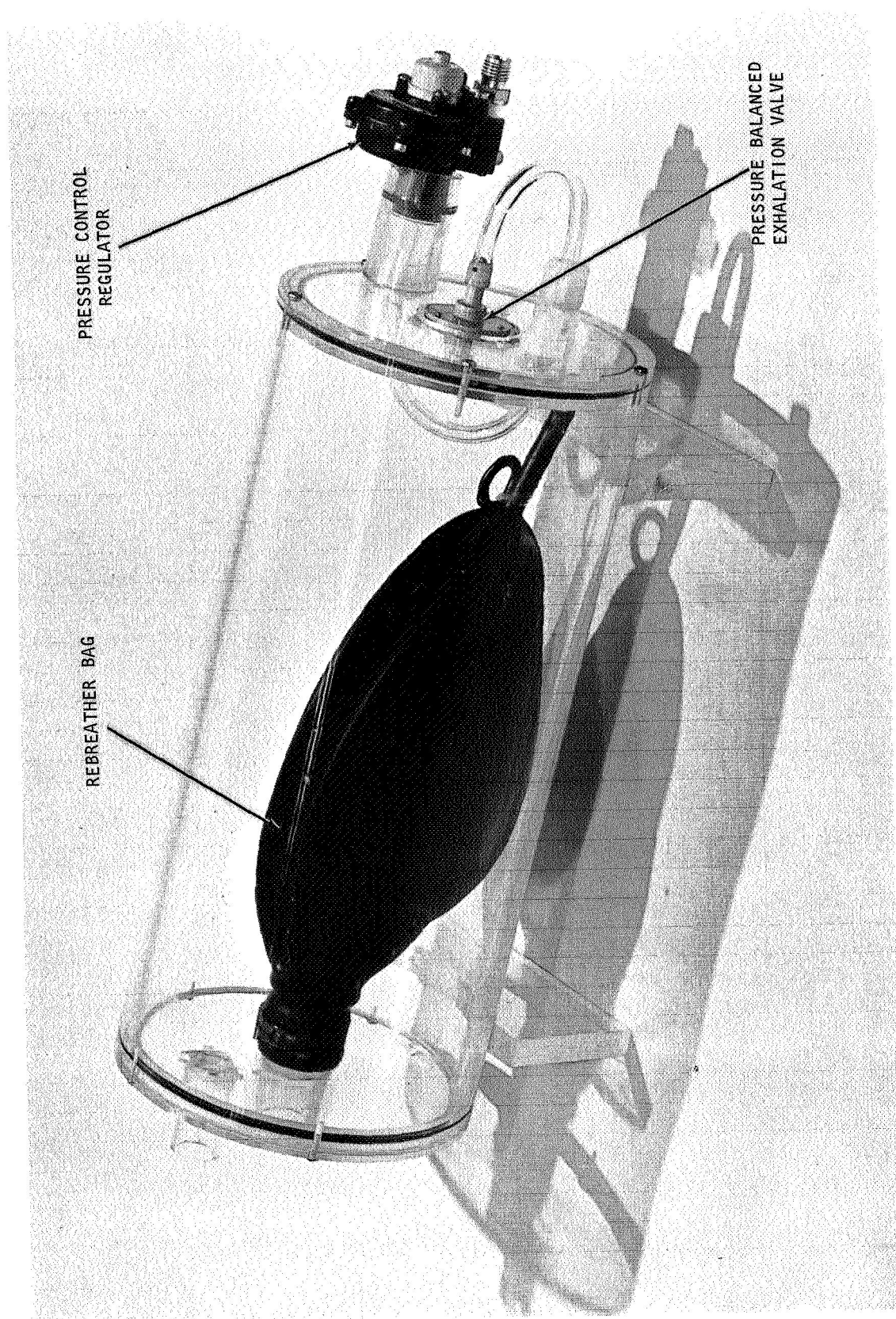


FIGURE 21 COUNTER-LUNG ASSEMBLY

breathing simulator is a modified animal respiration pump with adjustable rate, tidal volume, and inhalation/exhalation time ratios. The breathing loop relief valve is a Scott rubber diaphragm check valve having a cracking pressure of one-half inch of water. Figure 22 shows the breathing loop test schematic.

The breathing simulator was set to a rate of eighteen cycles per minute, 0.78 liters tidal volume, and inhalation for 40 percent and exhalation for 60 percent of the cycle. These conditions are felt to represent typical aviator respiration and are substantiated.<sup>1</sup> The breathing loop test incorporated a bleed of 0.85 liters per minute to simulate oxygen consumption and carbon dioxide removal from the loop. Air, rather than oxygen was used in the loop for testing. The breathing loop pressure and the counter-lung pressure were measured. Figure 23 is a photograph of the test loop.

Test Results - Aro-Buffalo Regulators. - The Aro-Buffalo pressure control regulator is a standard F2700 type regulator set to deliver 1.7 inches of water pressure at shutoff to the counter-lung for pressurizing the rebreather bag. It also provides a pressure of 2.4 inches of water to the pressure balanced vent valve. This vent valve is a normal mask type exhalation valve having a cracking pressure of 0.8 inches of water and a pressure drop of 1.3 inches of water at 1.7 CFM flow. The oxygen demand regulator is an F241-1320 regulator modified by removal of the safety pressure spring to have a cracking pressure of 0.4 inches of water below the reference pressure.

The test results of these components with the counter-lung and breathing simulator were as expected from the individual component test results. At inhalation the counter-lung pressure dropped to a minimum of 1.4 inches of water and at exhalation the pressure increased to a peak of 3.8 inches of water. The corresponding pressures in the loop were 0.5 inches of water minimum at inhalation and 4.2 inches of water at exhalation.

Only one significant problem was found during the testing. The oxygen demand regulator had a characteristic such that a significantly higher pressure was required to shut off the flow than was required to initiate flow. Thus the demand regulator tended to pressurize the system above the counter-lung pressure allowing flow out through the vent valve. This problem was solved by placing a restriction at the regulator outlet as shown in the schematic. The restriction was sized by trial and error so as not to cause the loop pressure to decrease below atmospheric pressure nor to allow the flow to pressurize the loop.

The operation of the vent valve between the breathing loop and the counter-lung was observed by increasing the tidal volume of the breathing simulator. When the tidal volume exceeded the bag volume, the loop pressure increased above the counter-lung pressure at the end of exhalation. This allowed flow from the loop through the vent into the counter-lung air space. Then, on inhalation, the bag would fully collapse and the loop pressure would drop below counter-lung pressure allowing flow in through the demand regulator. Since the tidal

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<sup>1</sup> Norris, P., Pilot's Respiration During a Standard Training Flight Profile, AD 486524, September 1964.

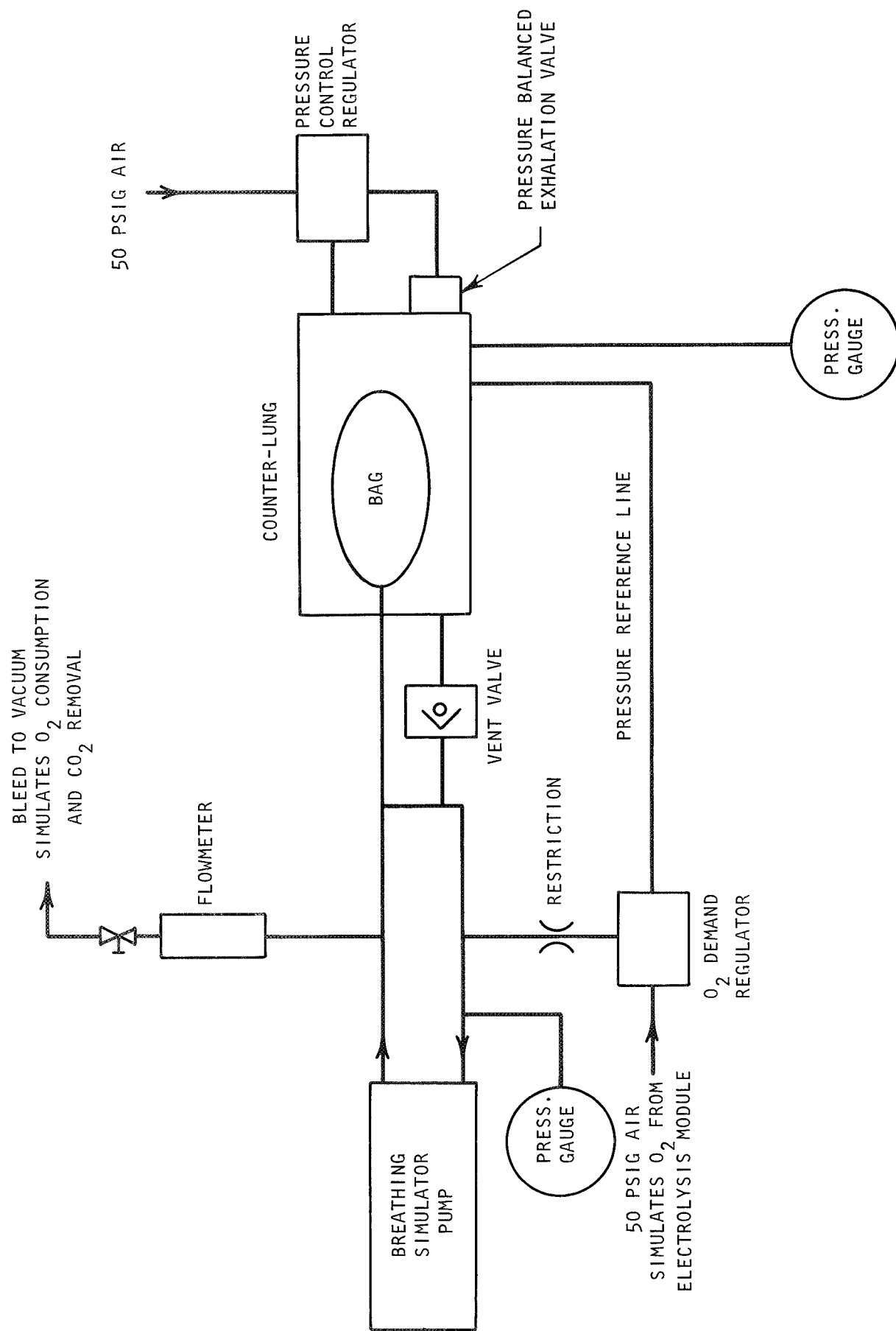


FIGURE 22 BREATHING LOOP TEST SCHEMATIC



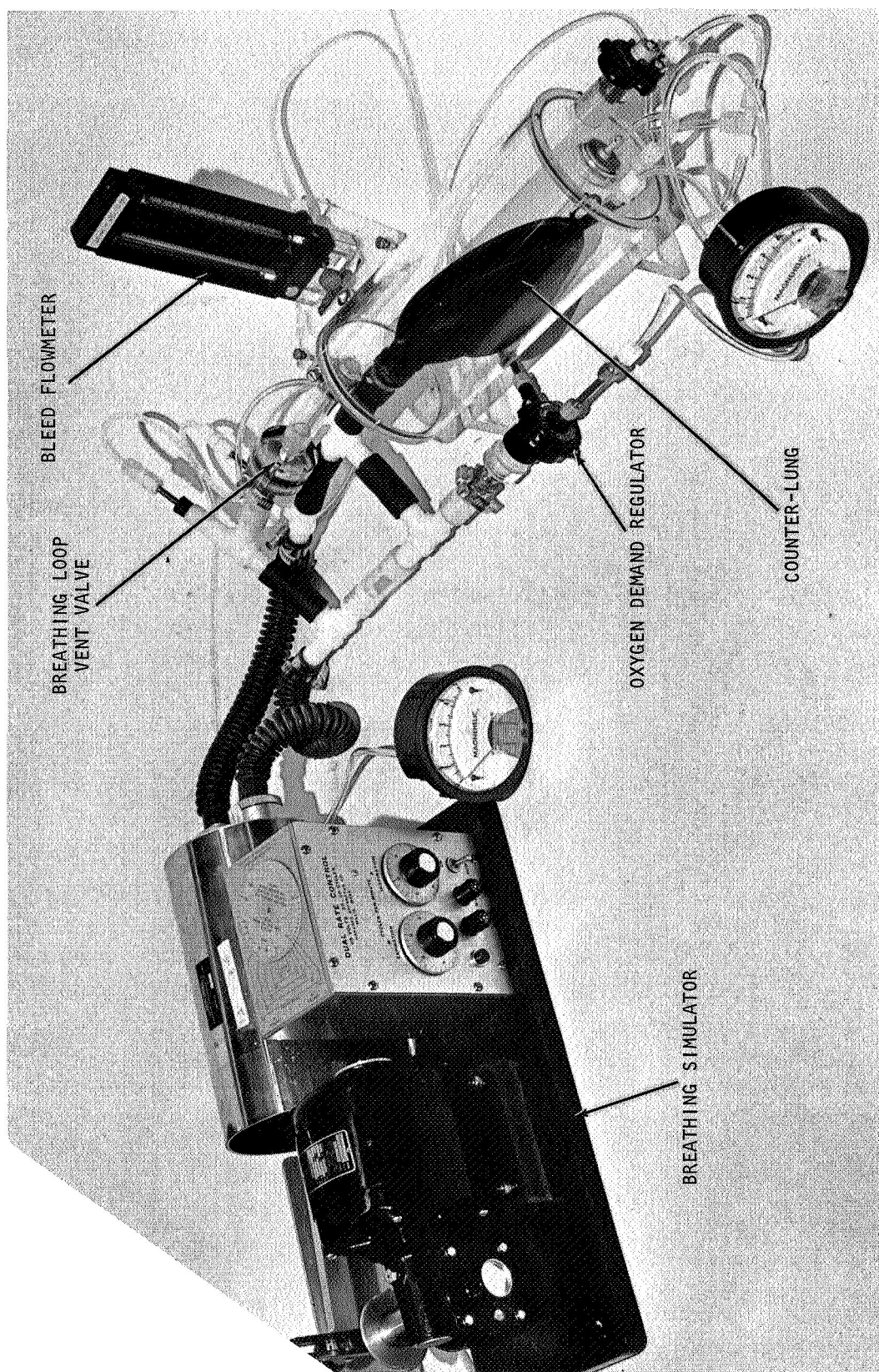


FIGURE 23 BREATHING LOOP TEST SET-UP

volume is less than the bag volume, the vent valve will not normally operate. However, it serves as a safety valve if, for example, exhalation begins with an inflated bag.

The breathing simulator was replaced with a standard mask and tried by the test engineer for short periods of time to get a "feel" for the system. Operation seemed satisfactory and comfortable. Operation can be improved by reducing the breathing loop pressure variations. At present, this variation is from 0.5 to 4.2 inches of water as mentioned previously. By reducing the exhalation valve pressure from 2.4 to 1.2 inches of water, a loop pressure variation from 0.5 to 3.0 inches of water will be obtained.

Test Results - Scott Aviation Regulators. - Breathing loop operation with the Scott regulators differed from that with the Aro regulators. The Scott components require compressed air to be metered into the counter-lung at a rate slightly higher than the maximum instantaneous breathing flow rate. The air exits from the counter-lung through a pressure loaded vent valve which is controlled by the regulator. The oxygen demand regulator which is in the same housing as the pressure control regulator is referenced to the vent valve pressure.

Initial test results of the Scott regulator showed that the oxygen demand regulator had a cracking pressure higher than the counter-lung pressure. An additional regulator would be required to raise the counter-lung pressure above the oxygen pressure for proper operation. This additional regulator would be a backpressure type regulator located at the control air bleed outlet from the pressure control regulator. The same effect was obtained by restricting the flow through the bleed port. The restriction could be varied to obtain any exhalation valve pressure desired. At exhalation valve pressures above 2.0 inches of water the oxygen demand regulator had a cracking pressure of 1.3 inches of water below the exhalation valve pressure. The exhalation valve had a pressure drop of 0.8 inches of water at 1.7 to 3.5 CFM air flow.

Operation with the breathing simulator gave results similar to those obtained with the Aro components. Counter-lung pressure varied from 1.8 to 4.0 inches of water from inhalation to exhalation while the corresponding loop pressures were zero and 4.2 inches, respectively.

The Scott components would require the modifications previously indicated, i.e., a backpressure regulator, and the added requirement for the metered air flow into the counter-lung. For this reason, and since the performance of the Aro regulator was comparable, it was decided to use the Aro components for integration into the breadboard system. The Scott components were used as a backup.

Recirculating Blower. - The recirculating blower is provided so that a steady flow higher than the breathing flow rate is passed through the carbon dioxide concentrator. This circulating flow minimizes temperature and humidity gradients in the module. The flow rate is 3.5 CFM and a pressure drop of 6 inches of water is the present design head. This allows 4 inches of water drop in the carbon dioxide concentrator, 1 inch in the check valve and 1 inch in the ducting. The Rotron Model R201 radial blade blower was selected to meet the specifications for the carbon dioxide concentrator recirculating loop.

The blower, rated at 115 volts, 400 Hz, had performance in excess of that required by the system. A blower control was designed to reduce the blower motor voltage such that the operating characteristics could be adjusted to coincide with the system requirements. Figure 24 shows the pressure flow characteristics for the blower operating at various voltages. The pressure drop through the carbon dioxide concentrator module and recirculating loop ducting was measured as a function of flow rate and is also shown in Figure 24 as "system characteristic." The intersection of the system characteristic curve and the blower characteristic determines the operating point. Since 3.5 CFM is the selected flow rate, the blower motor was operated at 70 volts. The blower control incorporates a continuously variable voltage adjustment which allows a wide range of operation.

Two of the original Rotron R201 blowers failed on test stands after less than 200 hours of operation. Internal short circuits developed in each motor. Inspection of the failed motors revealed that the liquids had worked their way into the windings through leakage paths from the blower housing to the motor housing where the seal was not satisfactory.

The problem was substantially reduced by the manufacturer by providing better sealing in all new units as well as repairing and sealing the failed units. The orientation of the blowers in the test stands was changed to place the motor above the blower housing. This kept liquids which might enter the blower housing from running into the motor even if leaks developed in the seals.

Heat Exchangers. - As shown on the system schematic, Figure 25, the heat exchangers are used only to provide a comfortable temperature and humidity to the pilot. The dehumidifier is a liquid-cooled heat exchanger which condenses some of the water from the gas stream. The condensed water is separated and vented from the system. The vent could be float-operated or timer-controlled to periodically drain a water sump.

The reheater is a regenerative type which reheats the dehumidified oxygen from nominally 40°F to 75°F. The warm oxygen going to the dehumidifier is nearly 120°F and is cooled slightly prior to the final dehumidification.

The heat exchanger requirements for the NAOS systems were established through consideration of the design requirements and operating characteristics of the breathing loop. Specifically, the following were considered:

1. Pilot's respiratory minute volume - 0.5 CFM (14 liters/min).
2. Peak instantaneous respiratory flow rate - 1.7 CFM.
3. Temperature of breathing oxygen to pilot - 60°F to 90°F (70°F to 80°F preferable).
4. Relative humidity of breathing oxygen to pilot - 50% maximum.
5. Breathing loop absolute pressure levels 3 psia to 15 psia. (14.7 psia used for designing heat exchangers.)

ROTRON S/N H 96709  
AIR AT 1 ATMOSPHERE  
400 Hz - VARIABLE VOLTAGE

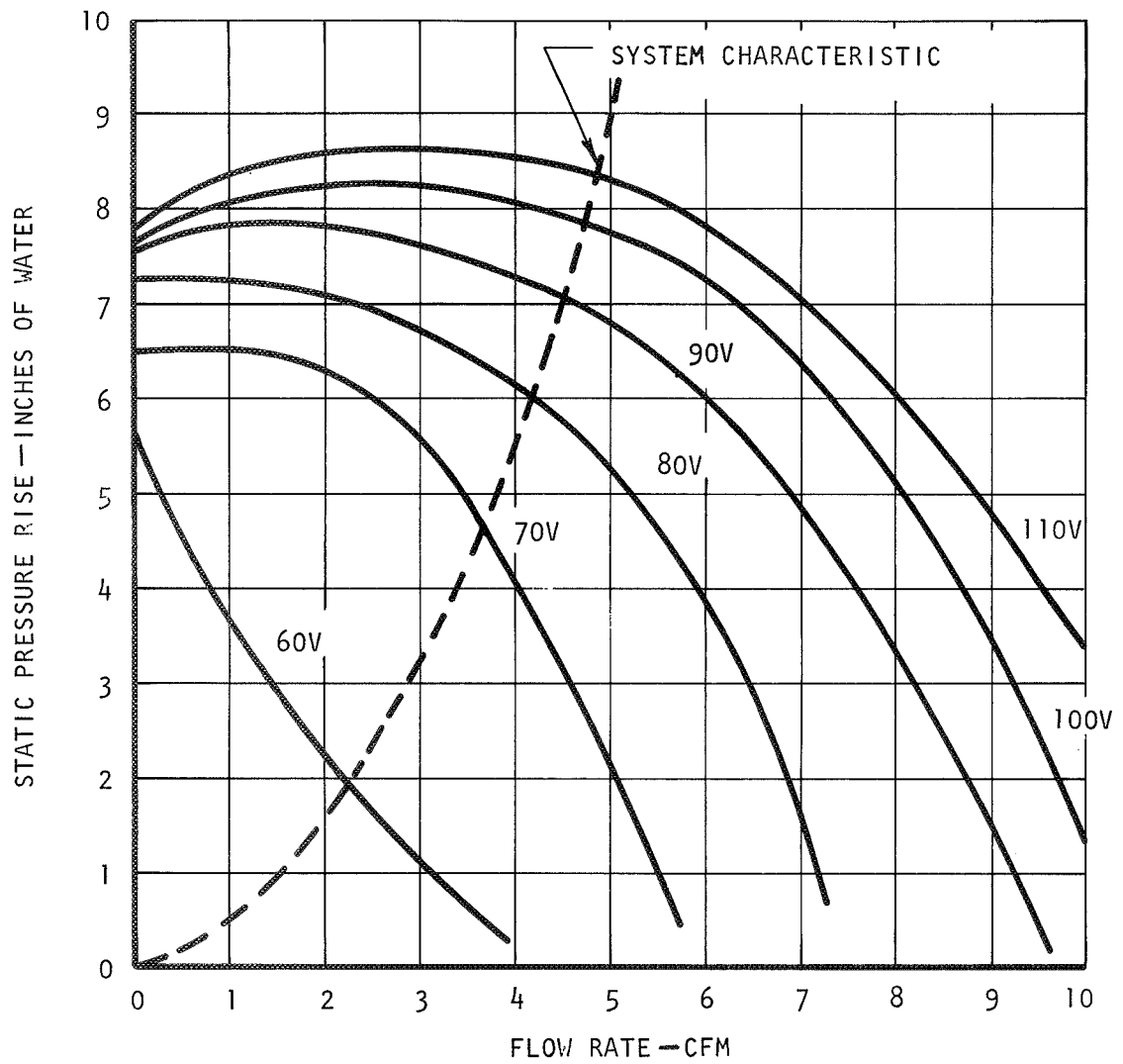


FIGURE 24 REBREATHING LOOP BLOWER PERFORMANCE

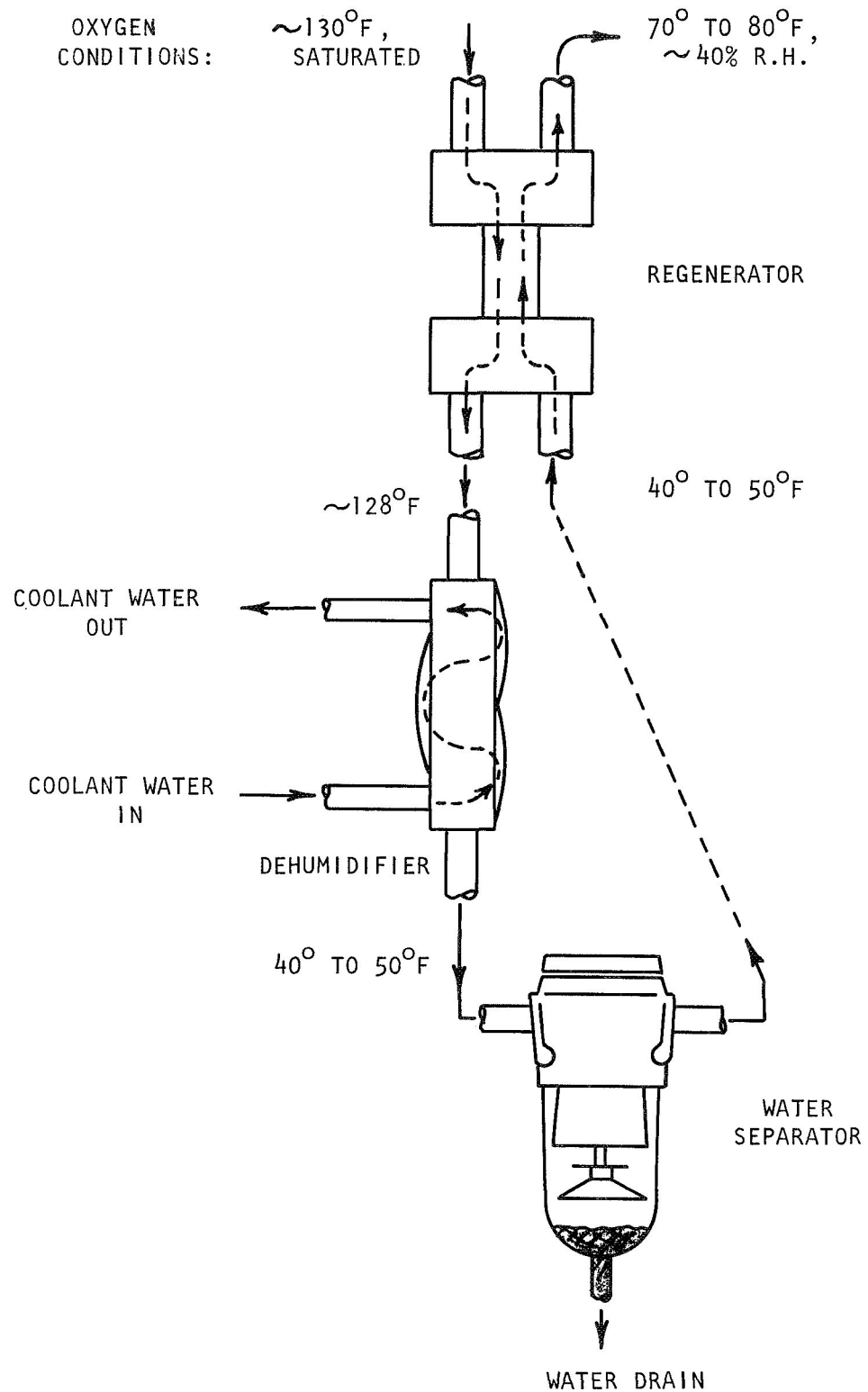


FIGURE 25 REBREATHING LOOP HEAT EXCHANGERS

6. Oxygen conditions entering heat exchangers, 130°F and 100% R.H. (CO<sub>2</sub> concentrator exit conditions).
7. Coolant available - water at 35°F to 45°F.

From the carbon dioxide concentrator exit to the pilot's mask, two cooling-heating stages are required for the oxygen stream. The oxygen which is at 130°F and 100% R.H. initially is cooled to a dew point of between 40°F and 50°F in a dehumidifier. The oxygen is then reheated in a regenerator, without the addition of water vapor, to achieve the desired temperature range and relative humidity for pilot comfort. A sketch of the heat exchangers is shown in Figure 25 along with the relative location of a separator to remove condensed water vapor. The condition of the oxygen stream is noted at several significant locations in the heat exchanger loop.

The regenerator was fabricated from readily available materials. It consisted of a corrugated stainless steel heat transfer element contained within a housing fabricated from acrylic plastic sheet and configured to achieve counterflow of the two streams. The oxygen on each side of the heat transfer element flows through the passages formed by the corrugated sheet and the acrylic housing. The dehumidifier is a water-cooled, cross-counter flow heat exchanger later changed to a shell and tube configuration after the completion of LBS evaluation testing. The cooling water makes four passes across the oxygen stream path while the oxygen makes a single pass through the heat exchanger. Internally, the heat exchanger consisted of stacks of corrugated fins, separated by parting sheets and configured to achieve the flow arrangements noted above. This heat exchanger was of an all stainless steel welded construction. It was originally designed and fabricated for another application and was oversized although the predicted performance was satisfactory.

The breathing loop heat exchangers were tested individually and in combination. The first test was that of the dehumidifier, alone. The dehumidifier outlet temperature was quite close to the cooling water inlet temperature. Thus the dehumidifier was a very effective heat exchanger and was much larger than need be for this application. The regenerative reheater was added for the second test. Figure 25 shows the test arrangement of the heat exchangers and the design conditions. Figure 26 is a photograph of the heat exchangers installed for the test.

A reasonably good heat and mass balance was obtained from this test. A notable result was that the reheater outlet temperature was much higher than desired. The reheater was found to have much higher heat transfer coefficients than calculated for design due to the relatively short length to diameter ratio of the flow passage resulting in turbulence due to the entrance effect. The requirement for the reheater was subsequently eliminated because heat transfer from the ambient was found to be sufficient to cause the mask inlet temperature to be near ambient temperature.

It was assumed in Table I that comfort conditions for breathing were similar to those for ambient air environment comfort conditions. This is probably not the case. Environmental comfort conditions involve body heat rejection considerations whereas heat exchange with breathing gases is of much less importance. Future



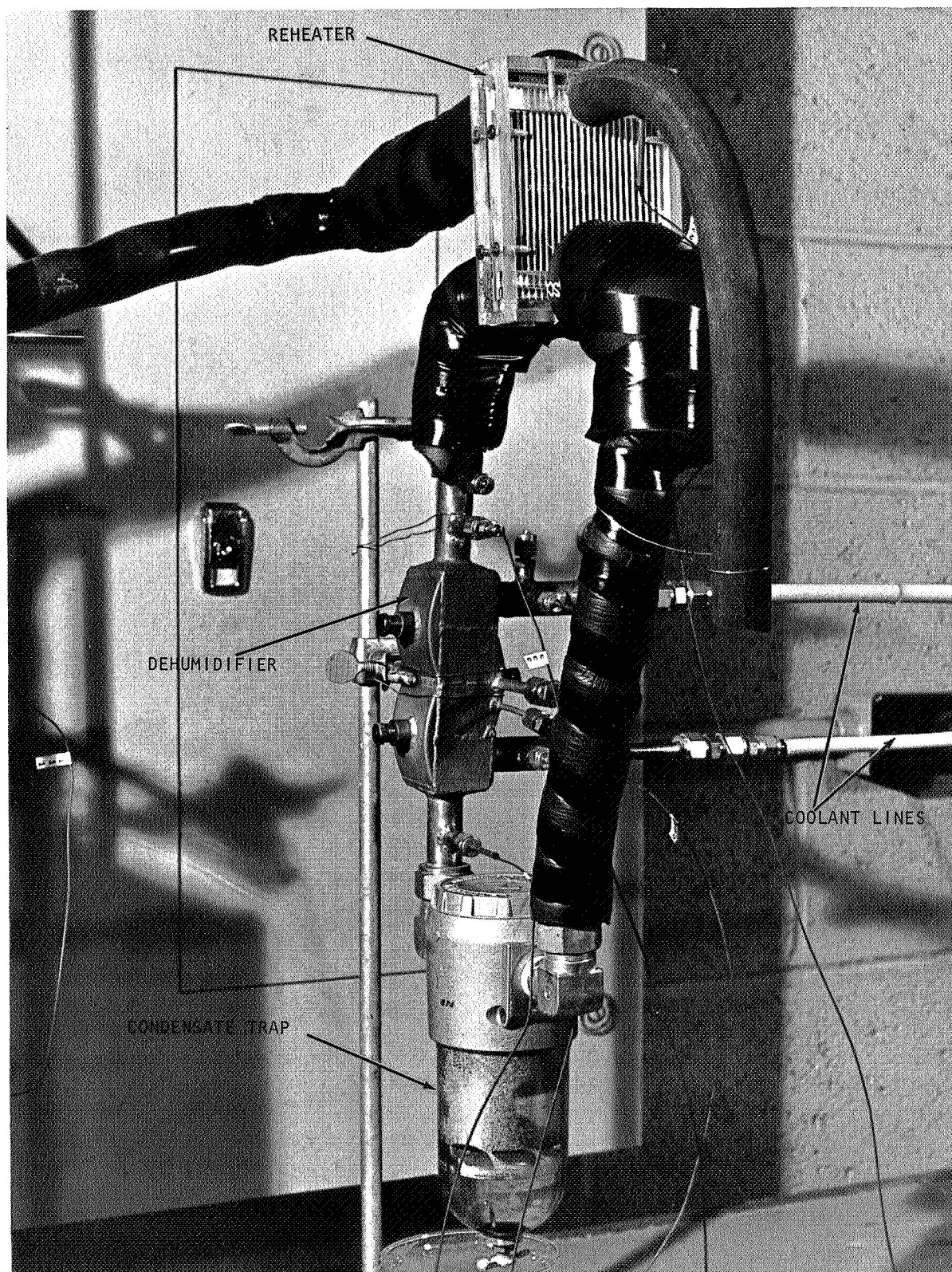


FIGURE 26 HEAT EXCHANGER TEST INSTALLATION

evaluations may show that oxygen temperature and humidity could likely have a wide comfort zone as long as the aviator's environmental air is maintained at a comfortable level.

### Hydrogen Eliminator

Since one of the waste products of the system is hydrogen, it is necessary to insure that the possibility of an explosion or fire is eliminated. A number of methods to solve this problem were considered. The general categories of solution are: 1) consume or react the hydrogen, 2) store the hydrogen and remove it after a flight, and 3) vent the hydrogen in a safe manner. Table VI shows the methods considered.

Hydrogen in air is flammable over the range of four to seventy-five percent hydrogen by volume. The ignition temperature is near 1000°F at atmospheric pressure. Thus, burning in air requires an ignition source, either electrical or catalytic such as a platinum wire. Hydrogen and air can be reacted at low temperature on a catalyst such as platinum or palladium. Enough excess air is required so that the heat of reaction is carried away at a reasonable temperature. If the outlet gas temperature is to be below 1000°F then the hydrogen percent by volume must be less than five percent at the inlet which is marginally combustible without a catalyst.

Another reactant would be CuO which would react with hydrogen to form water and metallic copper. This would require high temperatures ("red heat"). About eight pounds of copper oxide would be required and would have to be replaced after each flight.

The waste gases being a mixture of hydrogen, water vapor and carbon dioxide brings to mind the Bosch Reaction. This is the reaction of hydrogen and carbon dioxide on an iron catalyst to form water and carbon. This reaction requires temperatures about 1200°F. Since insufficient carbon dioxide to complete the reaction is in the waste gas, additional carbon dioxide must be carried on the flight. It may be possible to combine the Bosch Reaction with the above mentioned CuO reaction. In this case, all of the carbon dioxide in the waste gas is reacted with hydrogen and the remaining hydrogen is reacted with CuO. The water formed could be condensed and stored eliminating any venting requirement. This method is quite complex.

Storage of the hydrogen during the flight would be difficult since about forty standard cubic feet of hydrogen must be stored. A compressor could be employed to pump the gas to a high pressure tank for storage. The hydrogen absorbing properties of palladium at first seems attractive since it is reported to be able to absorb 870 times its volume of hydrogen gas. Even at this ratio, about thirty-six pounds of very expensive palladium would be required.

Lithium can be considered for hydrogen storage since its reaction with hydrogen is easily reversible. This reaction requires temperatures above 1000°F. Lithium also has the advantage in that it reacts with carbon dioxide and water and could result in eliminating any venting requirement. However, high temperature lithium also presents possible hazards.



TABLE VI

## HYDROGEN HAZARD ELIMINATION METHODS

Method	Comments
1. Burn in air	Excess air required to cool products igniter required
2. React with air on catalyst	Excess air required to cool products
3. $\text{H}_2 + \text{CuO} \longrightarrow \text{Cu} + \text{H}_2\text{O}$	Required high temperatures, must replace CuO after flights
4. $2\text{H}_2 + \text{CO}_2 \xrightarrow{\text{Fe}} 2\text{H}_2\text{O} + \text{C}$	Requires high temperatures and must carry $\text{CO}_2$ for reaction
5. Combine (3) and (4) above, condense water formed	Requires high temperatures and coolant for condenser but eliminates all venting
6. Store waste gases	Requires compressor and tank
7. Absorb in palladium	Heavy and expensive
8. $\text{H}_2 + 2\text{Li} \rightleftharpoons 2\text{LiH}$	Requires high temperature but can regenerate
9. Vent $\text{H}_2$ to engine	Gets well diluted
10. Mix with air and vent overboard	Non-combustible, no hazard

The third method, that of venting the hydrogen, is the simplest. The hydrogen must be vented to a safe place where it could not accumulate. Venting directly to the jet engine inlet would insure mixing and dilution with very large quantities of air. If this cannot be done, then mixing with air to below the combustible limit will allow venting anywhere.

It appears that diluting the hydrogen with air to below the combustible limit would allow direct venting with no hazard. However, a hydrogen-air catalytic reactor will be utilized since this would remove the hydrogen from the exhaust gases in the simplest manner. Again standard or near standard components were sought although a flight weight and packaged system would require a new design.

A hydrogen reactor was purchased from MSA Research. This unit included an air blower to mix air with the NAOS hydrogen exhaust, a heated catalytic reactor which would cause the hydrogen to react with oxygen in the air-hydrogen mixture, and a heater control to maintain the catalyst bed at 600°F.

The air blower supplies 4.3 CFM to mix with the nominal 0.03 CFM of hydrogen exhausted by the system. Thus a mixture of near one percent concentration of hydrogen enters the catalytic reactor. The low hydrogen percent in the air assures that the mixture would not be combustible or explosive.

The MSA unit was tested by measuring the outlet air dew point temperature with and without the hydrogen flow input. From the dew point temperatures the change in moisture content of the exit air stream could be related to the hydrogen reacted to form water. Within the measurements' accuracy, this unit was found to react all of the inlet hydrogen. The MSA unit was too large and complex, therefore it was decided that a much smaller reactor could be designed and fabricated using a more suitable catalytic bed design.

Samples of palladium-treated asbestos sheet were obtained from Ucinite Division of United-Carr. This material is used commercially in the vent of self-cleaning ovens to react hydrocarbons. This material was found to react hydrogen and air at room temperature and therefore would be usable in a hydrogen eliminator without the requirement for the addition of heat.

A unit was fabricated having a catalyst bed 1.5 inches in diameter and 3.0 inches long. The bed is a spiral winding of the palladium-treated asbestos with a corrugated steel spacer for gas passage. The hydrogen is pre-mixed with air upstream of the bed by a propeller type baffle. Figure 27 is a photograph of the unit.

The unit was tested by measuring the air and hydrogen flowrates and the inlet and outlet temperatures. The quantity of hydrogen reacted was then computed from the heat of reaction of the hydrogen and oxygen in the air.

A heat balance showed that 85 percent of the hydrogen was reacted. However, the heat losses lower the measured outlet temperature and consequently the true percentage of hydrogen reacted is larger than this amount. The test of the hydrogen reactor shows that if such a device is required it can be made reasonably small and requires only air to operate it.

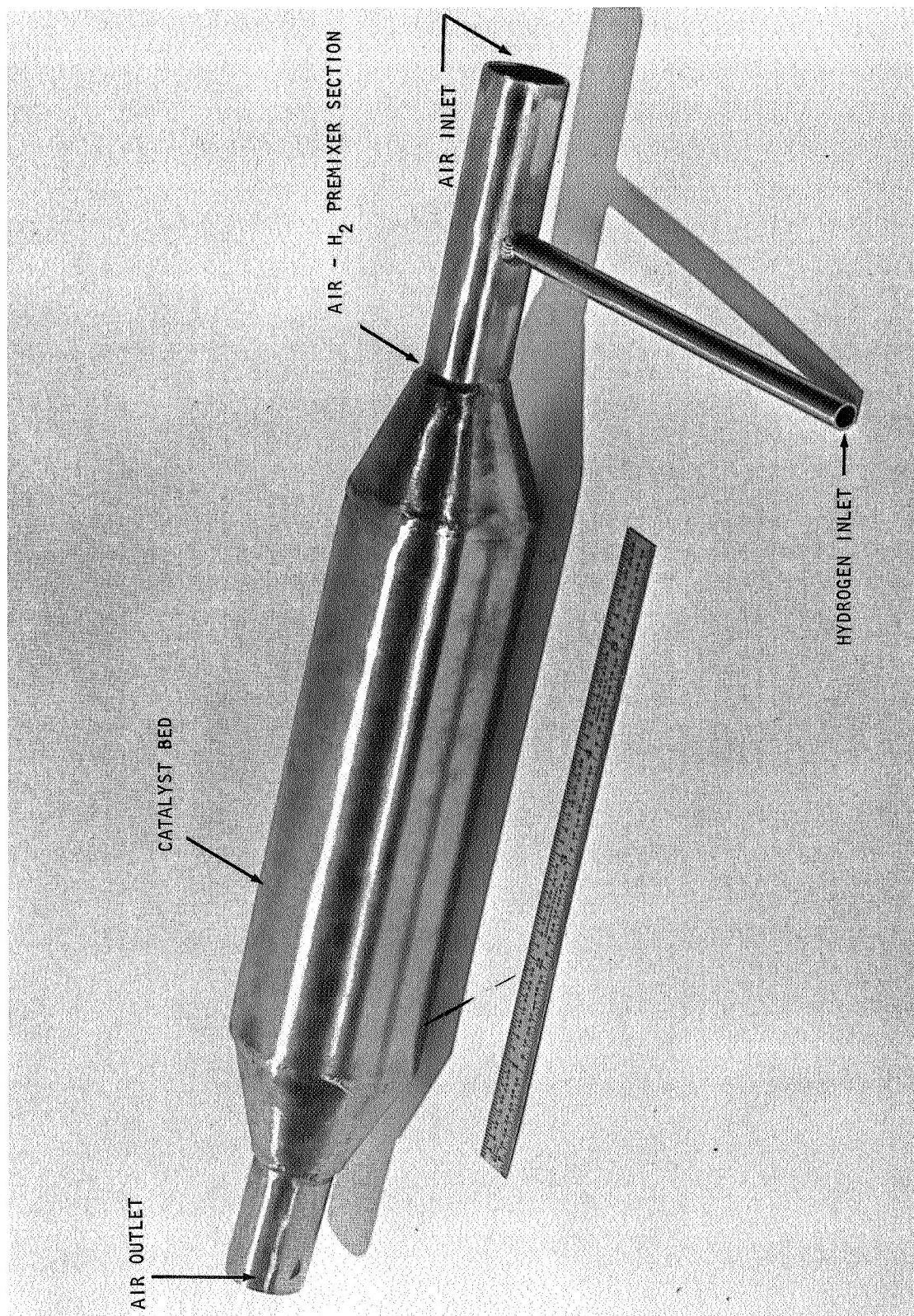


FIGURE 27 HYDROGEN REACTOR

## LABORATORY BREADBOARD SYSTEM TESTS

The purpose of the breadboard system was to determine system performance and component interactions, and to identify and solve any system integration problems. This was most economically carried out prior to final designs or refinements. The breadboard system has components functionally connected without regard to final orientation or packaging. In this way sufficient instrumentation to monitor interface conditions and determine system performance was easily incorporated. In addition, components were easily added or changed. There were two phases in the breadboard system testing.

Phase 1 involved endurance testing of the electrochemical components separately with little change in the test rig during the tests. Phase 2 was an evolution into the final breadboard systems by the addition of components so that interaction problems could be more readily identified and solved.

### Endurance Tests

The endurance test rigs were nearly identical to the previously designed electrolysis module and carbon dioxide concentrator module test rigs. A major difference is that for the electrolysis module the current control unit was the unit fabricated as a breadboard for the power conditioning development task. This allowed tests to be conducted with the automatic pressure control as well as manual current control. Another difference was that for the carbon dioxide concentrator module, the Kordes-Marko bridge network was not employed in the load control circuit. Instead, a breadboard of the load control developed for the flight breadboard system was used.

Electrolysis Module. - Figure 28 shows the laboratory breadboard system as configured for endurance testing. The endurance testing of electrolysis module No. 2 was accomplished as part of the Breadboard System Test Plan. The operating conditions selected for the endurance test were as follows:

Current Density:	80 to 100 ASF
Stack Temperature:	165°F (avg.)
Oxygen Pressure Level:	14 psig (avg.)
Oxygen to Hydrogen Pressure Differential:	0 to 1.5 psid

The endurance test of electrolysis module No. 2 was terminated after 1,562 hours of operation. This operating time exceeded, by five days, the scheduled sixty-day test duration. Figure 29 shows the average cell voltage and current density as a function of time for the entire test period. The operating conditions of the module during the endurance tests are also shown on this figure.

The average cell voltage ranged from 1.8 to 2.3 volts. The module operated for a total of 630 hours at a current density of 100 ASF. During 57 percent of this time the average cell voltage remained at less than 2.0 volts. Eight hundred eighty (880) hours of module testing was conducted at a current density of 80 ASF. During 88 percent of this time the average cell voltage remained at less than 2.0 volts. Table VII lists elapsed time, causes and corrective



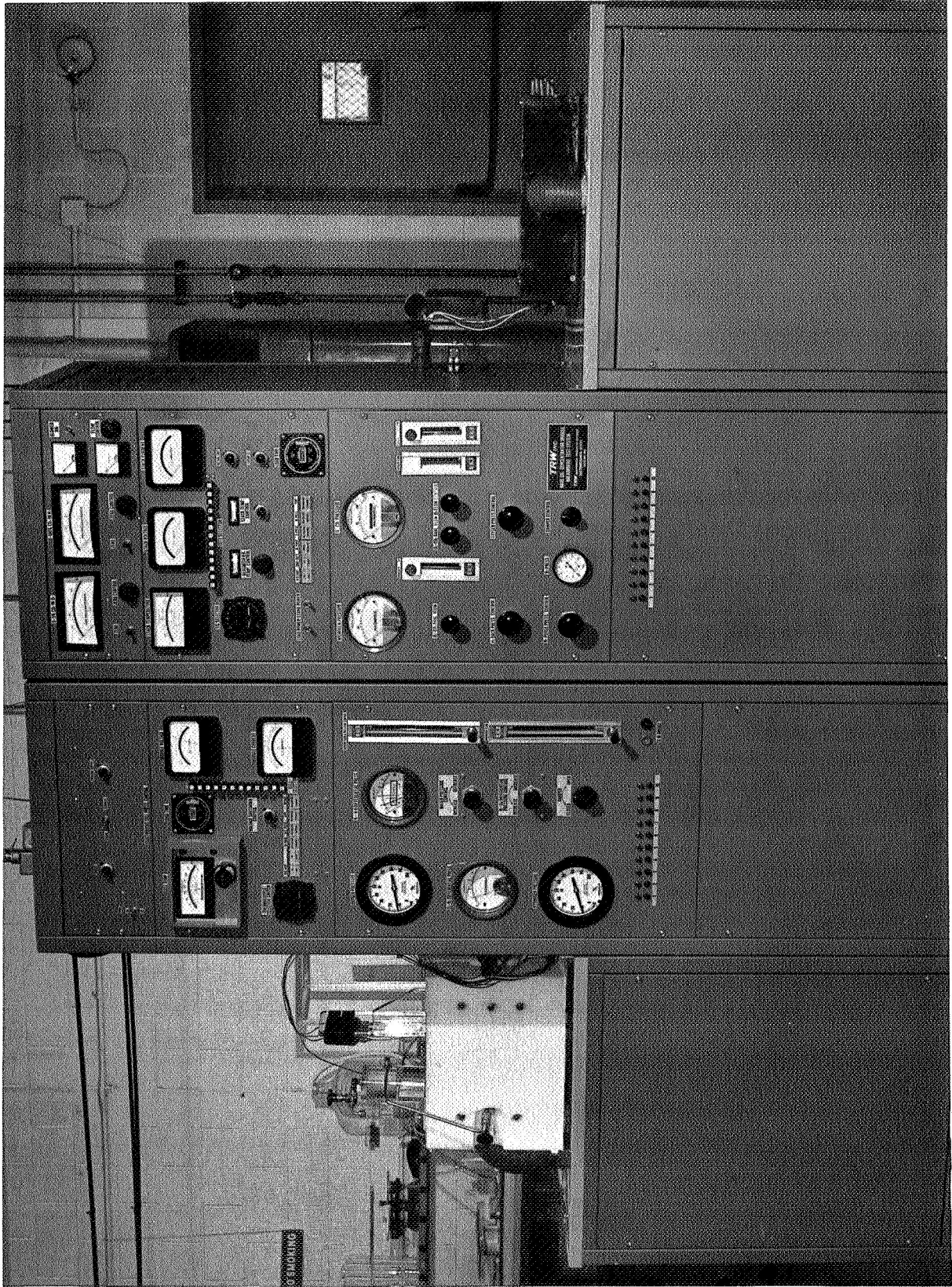
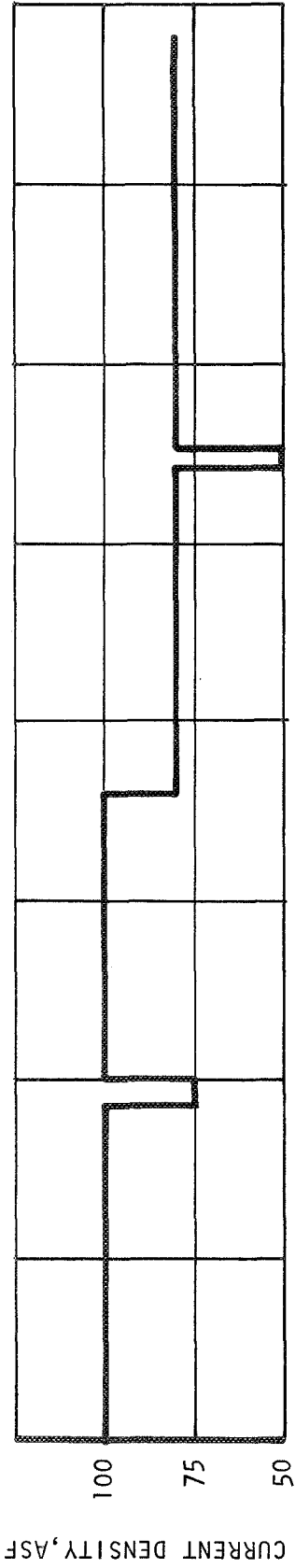


FIGURE 28 LABORATORY BREADBOARD SYSTEM TEST STAND - PRELIMINARY ENDURANCE RUN CONFIGURATION



AVERAGE OPERATING CONDITIONS

STACK TEMPERATURE: 165°F  
 OXYGEN PRESSURE: 14 PSIG  
 O<sub>2</sub> TO H<sub>2</sub> PRESSURE DIFF.: 0 TO 1.5 PSID

NOTE: SEE TABLE FOR SHUTDOWN SUMMARY

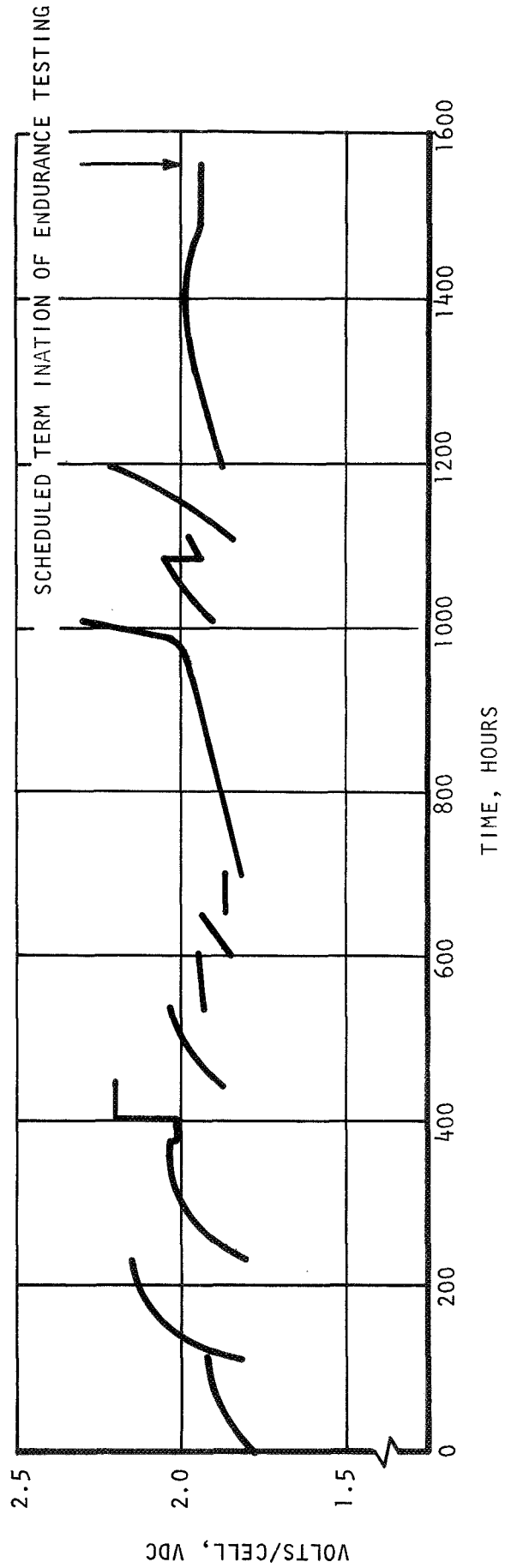


FIGURE 29 ELECTROLYSIS MODULE NO. 2, ENDURANCE TEST

TABLE VII  
BREADBOARD SYSTEM ELECTROLYSIS MODULE  
SHUTDOWN SUMMARY

<u>Elapsed Time, Hours</u>	<u>Cause of Shutdown</u>	<u>Corrective Action</u>
113.1	Differential pressure control malfunction; module flooded and flushed	Module recharged
231.7	H <sub>2</sub> vent solenoid valve failure; module flushed	Module recharged
375.1	Water cavity vent solenoid valve failure; water cavities flushed	Restart
445.2	Differential pressure control malfunction; module flushed	Module recharged
538.4	Plant power shutdown	Restart
602.3	Plant power shutdown	Restart
655.2	Module flush; overvoltage shutdown	Restart
668.0	Differential pressure shutdown	Restart
693.5	Overvoltage shutdown	Module recharged
700.5	Crossleak between O <sub>2</sub> and H <sub>2</sub> cavities in Cell No. 1	Rebuilt Cell No. 1; module recharged
1011.5	Feed water solenoid valve malfunction with electrolyte back-flush resulting in overvoltage shutdown	Restart
1109.2	Voluntary shutdown	Module recharged
1200.0	Overvoltage shutdown; module completely dry; possible feed water solenoid malfunction	Restart
1230.0	Feed water solenoid valve malfunction, condenser trap leak	Valve and trap replaced, module restart
1499.9	Momentary power failure	Restart
1562.0	Scheduled termination of endurance test	

action taken for the various module shutdowns. Only two shutdowns occurred during the final fifteen days of testing. The first was due to a solenoid valve malfunction and a condenser trap leak while the second was caused by a momentary power failure.

During the 1,562 hours of testing, the module was recharged six times with fresh electrolyte. The longest period without recharge was 453 hours and occurred immediately prior to schedule test termination. Most recharges were required after electrolyte was flushed out of the cell matrices during module flooding. The latter normally was caused by solenoid valve and/or differential pressure control malfunctions. Solenoid valve or differential pressure control malfunctions accompanied by cell flooding and/or flushing invariably resulted in accelerated performance degradation. Each time a module recharge was eventually necessary to restore original performance. No apparent reason for the crossleak in Cell No. 1 (at 700.5 hours) could be determined at module disassembly. The water cavity spacer screen and the two asbestos support screens, all made from polypropylene, had melted immediately opposite the crossleak location. The three screens and the asbestos matrices of Cell No. 1 were replaced prior to reassembly of the module. A close inspection of the cell components at disassembly showed no appreciable sign of corrosion. After termination of the endurance tests, the electrolysis module was removed from the test stand and was filled with electrolyte.

CO<sub>2</sub> Concentrator Module. - Module No. SN02 was endurance-tested in the breadboard test rig and accumulated 528 hours on load. The performance of the module is presented in Figure 30. A significant portion of the testing was accomplished at an operating point similar to that expected to be used during breadboard testing. The operating point is summarized in Table VIII. The shutdown history of the module is summarized in Table IX.

#### Breadboard System Integration

At the conclusion of the endurance testing of the electrolysis module and the carbon dioxide concentrator, the test stand was modified and interconnected to make a complete breadboard of the system. The modifications included the addition of the rebreather loop components, i.e., counter-lung, oxygen demand regulator, dehumidifier and water separator. Oxygen from the electrolysis subsystem was connected to the oxygen demand regulator, and the hydrogen line was connected to the carbon dioxide concentrator. The breathing simulator was added to the system to "close the loop" in the rebreather. The regenerative heat exchanger intended for reheating the oxygen after leaving the dehumidifier was not installed in the breadboard because calculations showed that the oxygen would exchange heat with the environment to reach near ambient temperature by the time it reached the aviator. Figure 31 shows the breadboard system schematic.

Water Electrolysis Subsystem (WES). - The water electrolysis subsystem is composed of the electrolysis module, water reservoir, oxygen pressure control, pressure balance regulation, a cooling loop, and water vapor condensers and traps. A solenoid valve between the water reservoir and electrolysis module is closed when the system is not in operation to prevent flooding of the cells. During operation this valve is open and the proper differential pressures are maintained by the differential regulator in the oxygen line and the backpressure regulator in the hydrogen line.



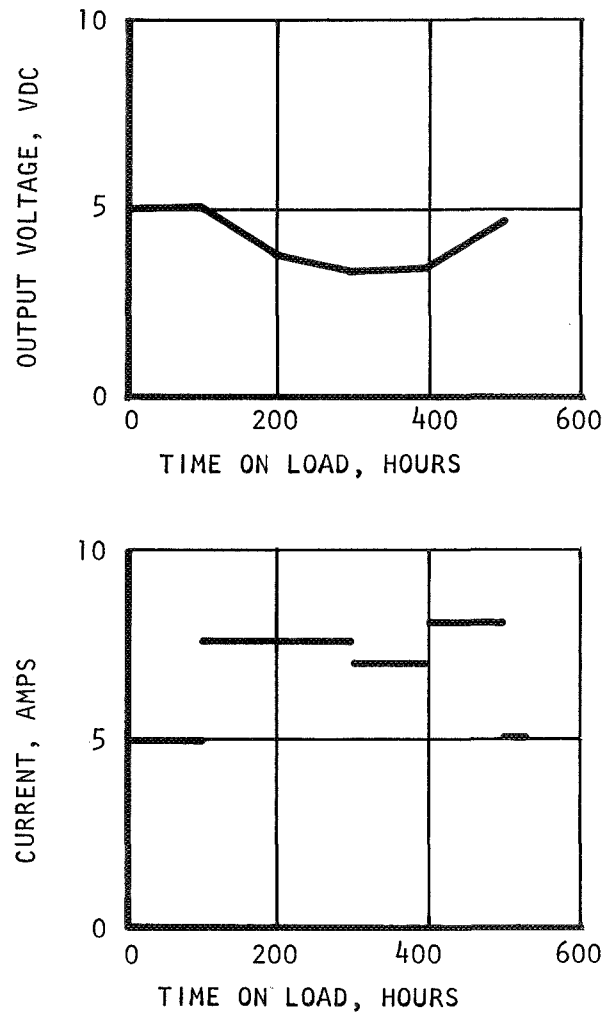


FIGURE 30 CO<sub>2</sub> CONCENTRATOR MODULE NO. SN 02, ENDURANCE TEST

TABLE VIII

CO<sub>2</sub> CONCENTRATOR BREADBOARD SYSTEMENDURANCE TEST OPERATING POINT

CO <sub>2</sub> Transfer Rate	0.43 sl/min ±.04
Current	7.6 amperes
Temperature	103°F ±4
O <sub>2</sub> Circulation Rate	2.5 CFM
H <sub>2</sub> Flowrate	1.2 sl/min

PERFORMANCE OF MODULE

%CO <sub>2</sub> at O <sub>2</sub> Exit	0.3% ±.2
Voltage Output	3.8 volts ±.2

TABLE IX

CO<sub>2</sub> CONCENTRATOR ENDURANCE TEST  
SHUTDOWN SUMMARY

Elapsed Time, Hours		
32.0	Crossover Air-Heater Blower, crossleak	Recharged Install H <sub>2</sub> line humidifier, repair TC and recharge
	H <sub>2</sub> maldistribution	Humidify overnight
50.6	H <sub>2</sub> maldistribution H <sub>2</sub> maldistribution SN022 - start	H <sub>2</sub> humidifier removed Rebuild 30 mil F.C.B.'s and modified H <sub>2</sub> passages
	H <sub>2</sub> maldistribution	Rebuild
51.1	SN023 - start	Series flow for H <sub>2</sub> Pre-humidifier for H <sub>2</sub>
123.1	H <sub>2</sub> pre-humidifier failure by crossover	New flask and gas dispersion tube design
147.7	Crossleak	Recharge, operational temperature lowered
247.7	Flooded out stack	Raise stack temperature
269.3	Crossleak	Recharged
272.5	No. 1 cell negative	Restart
278.2	No. 1 cell negative	Restart
358.7	No. 1 cell negative	Recharged, retorqued
455.9	Crossleak, circulating pump failure	Replaced pump
528.0	Start Breadboard System Testing	

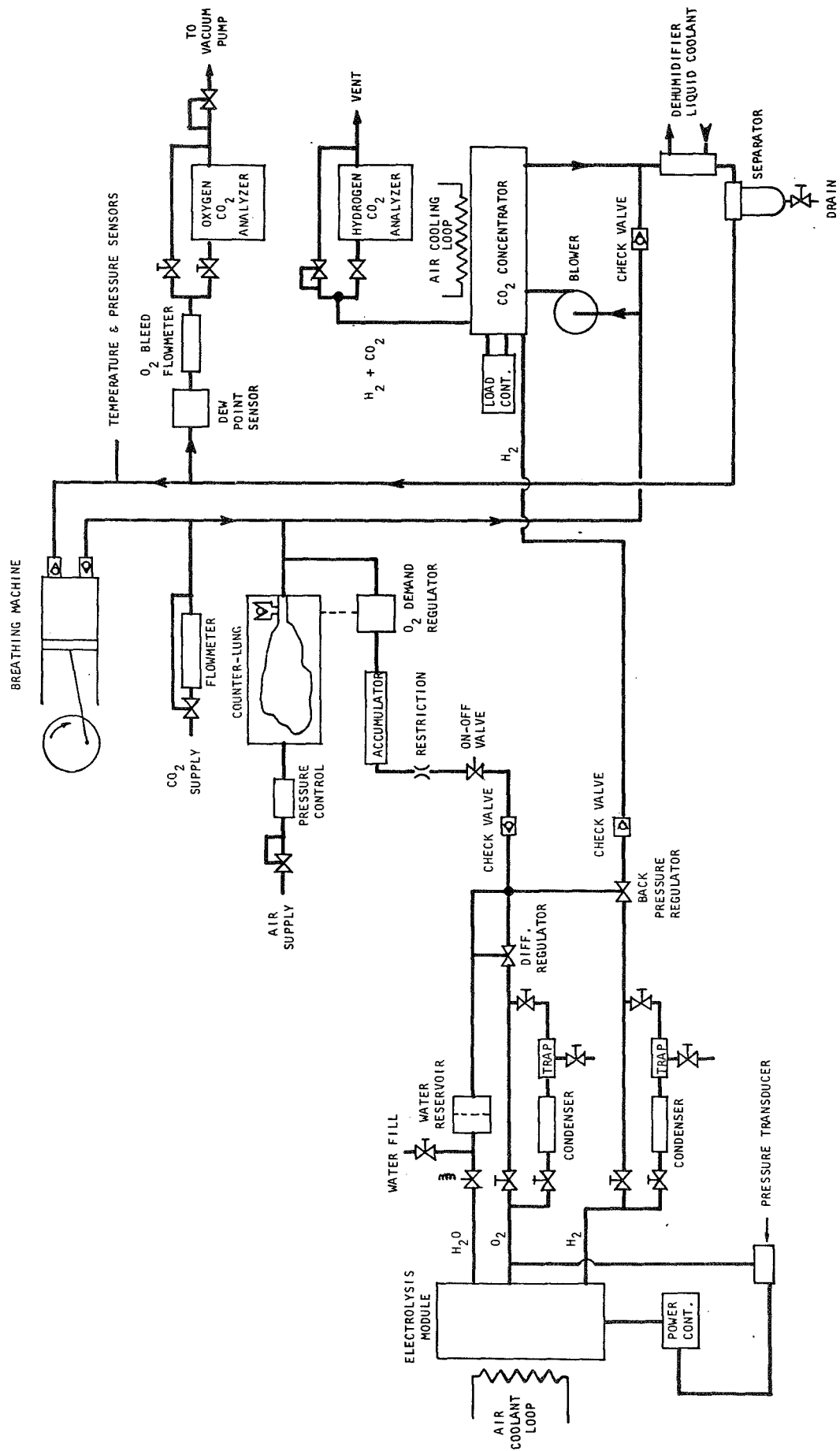


FIGURE 31 NAOS - LABORATORY BREADBOARD SYSTEM SCHEMATIC

The oxygen pressure control senses the oxygen pressure with a transducer and uses this signal to adjust the current flow into the electrolysis module. The characteristics of this control are such that the current remains constant as the pressure rises to a set pressure. At this pressure the current decreases linearly with pressure until the current is zero at the shutoff pressure.

The cooling loop incorporates a blower, heater and temperature controller. The controller regulates power to the air heater to maintain the electrolysis module at constant temperature.

The condensers and traps in the oxygen and hydrogen lines are used to condense moisture at high cell operating temperatures. The condensers can be bypassed when not used. The check valves prevent backflow into the electrolysis module when the system is not operating. The shutoff valve in the oxygen line prevents oxygen loss through the demand regulator in the event that the rebreather loop is opened. The restriction and accumulator were added to the oxygen line to damp out pulsations caused by the periodic operation of the demand regulator.

CO<sub>2</sub> Concentrator Subsystem (CDCS). - The carbon dioxide concentrator subsystem is composed of the carbon dioxide concentrator module, oxygen circulating loop, including a blower and check valve, an electrical load control, and a cooling system. The circulating loop provides for continuous oxygen flow through the carbon dioxide concentrator independent of the periodic breathing flowrates.

The load control maintains a constant current flow through the concentrator and load resistors independent of the concentrator voltage. The cooling system incorporates a temperature controller which turns an air blower on when the concentrator reaches a set temperature.

Rebreather Subsystem (RS). - The rebreather loop contains the counter-lung, oxygen demand regulator, dehumidifier and water separator. The counter-lung incorporates an air pressure control and a breathing loop vent valve. The oxygen demand regulator is referenced to the counter-lung pressure. The dehumidifier reduces the dew point of the oxygen delivered to the breathing machine to near 50°F. The coolant is water supplied from a cooler with temperature control. The water separator removes the condensed water and stores it in a sump. The sump has a manual drain valve.

The laboratory breadboard includes a breathing simulator which incorporates adjustable tidal volume, breathing rate, and variable inhalation/exhalation rate ratios. A carbon dioxide supply flowmeter is used to add carbon dioxide to the system at the design metabolic rate. The oxygen bleed flowmeter is used to duplicate oxygen metabolic consumption. An analyzer is installed in the oxygen line to measure carbon dioxide content in the breathing loop. Another analyzer in the hydrogen line is used to check carbon dioxide removal rates versus the carbon dioxide flowrate added to the system.

Figure 32 is a photograph of the laboratory breadboard. Figure 33 shows some of the rebreather components installed.

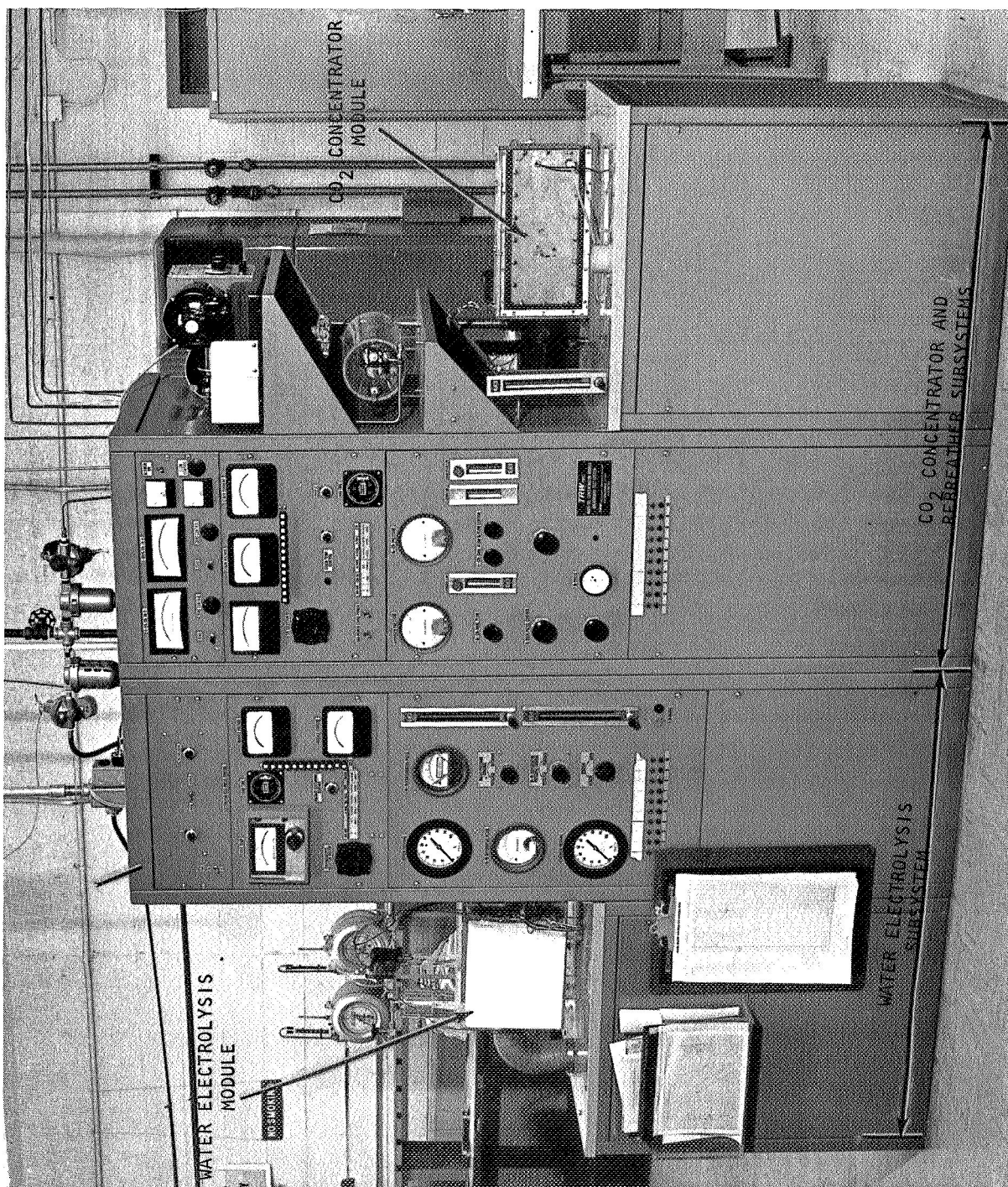


FIGURE 32 NAOS LABORATORY BREADBOARD SYSTEM





FIGURE 33 NAOS LABORATORY BREADBOARD REBREATHER COMPONENTS

## System Testing

Interface Tests. - Prior to conducting tests with the entire breadboard system, the electrolysis module oxygen pressure control was pre-set to shut off the current to the electrolysis module at 80 psia. The pressure control band was selected to be 6 psi. This would allow the current to be steady with small pressure variations, yet allow a full current of 28 amps at 74 psia.

The set point could be shifted by a manual potentiometer adjustment and was found to have the same 6 psi range between shut off and full current at 55 psia also. For nearly all of the tests that follow, the pressure control remained at the 80 psi shut off setting. At the design current of 22.3 amps, the resulting oxygen pressure was 75 psia.

The first tests involved examining the effects of the periodic oxygen flow demands of the demand regulator on the electrolysis subsystem. It was observed that the pressure balancing regulators at the electrolysis module had dynamic characteristics such that slight variations in the hydrogen-water pressure differential would occur when the demand regulator periodically opened.

These periodic variations in pressure difference would cause some degree of flexing of the water feed matrix within the electrolysis module and therefore should be minimized. By valving in and out the relatively large traps in the oxygen and hydrogen lines upstream of the regulators, it was shown that the upstream volume had very little effect on these pulsations. Operation at pressure levels between 50 and 80 psia showed little effect of pressure level on the differential pressure variations.

It was concluded that the pressure variations were characteristics of the regulators and the variations could eventually be eliminated by using different regulators with faster response characteristics. In order to reduce the pressure variations in the existing breadboard, a restriction in the oxygen line was added upstream of the demand regulator. The restriction smoothed out the pulsating flow demands downstream so that upstream pressure variations were very slight, about 0.1 psi compared to about 0.5 psi without the restriction.

However, the restriction caused the pressure variations downstream to be very large due to the relatively small volume in the line between the restriction and the demand regulator. The addition of an accumulator fabricated from a six inch length of one-half inch diameter tubing was found to give tolerable pressure variations of about 20 psi upstream of the demand regulator.

Another test of the pressure balance regulators under transient conditions was to simulate an aviator removing his mask without shutting off the oxygen supply to the demand regulator. Since the system operates with a safety pressure of about 1.5 inches of water, removing the mask would allow a large oxygen leakage unless the supply were shut off. To duplicate this effect, a hose was disconnected from the breathing machine. Since very little storage volume is in the present system plumbing, this large leakage rate caused the oxygen supply pressure to drop from 75 psia to 45 psia in six seconds. During this interval the hydrogen-water differential pressure shifted from a nominal 1.5 psi to 2.5 psi and the oxygen-hydrogen differential pressure changed from a nominal



near zero to 2.0 psi. These changes are considered to be entirely safe and satisfactory for this severe test.

Start-up. - The start-up procedure for the breadboard system was to simulate the procedure which is envisioned for an aircraft system. First, the electrolysis subsystem is energized. This turns on the electrolysis power control and temperature control. The air supply to the counter-lung, and the coolant flow to the dehumidifier is turned on. As the electrolysis module outlet pressure rises to near 80 psia the pressure control decreases the current. When this point is reached the manual supply valve is opened to connect the electrolysis subsystem to the demand regulator.

The demand regulator, which is referenced to the counter-lung pressure, then pressurizes the rebreather loop to the safety pressure of 1.5 inches of water. The Carbon Dioxide Concentrator Subsystem is then energized. This closes the external electrical circuit through the load control to maintain 7.6 amps current flow. At the same time the oxygen circulating blower and carbon dioxide concentrator temperature control are turned on. The breathing machine is turned on as well as the oxygen bleed and the carbon dioxide inflow to simulate metabolic consumption of oxygen and rejection of carbon dioxide.

In a final aircraft system, the start-up would involve two steps. The first would be to turn on a switch energizing the electrolysis subsystem. When the oxygen pressure rises to the design level an indicator lamp would signal that the system is ready. At this point the aviator would don his mask and turn on a second switch which would open the oxygen valve to the demand regulator and energize the Carbon Dioxide Concentrator Subsystem. He could now begin breathing with the system.

In order to demonstrate operation of the nitrogen vent valve in the counter-lung, a series of tests were conducted to simulate the purging of the system at start up. The rebreather bag in the counter-lung has a volume of one liter. The nitrogen vent operation was obtained by adjusting the tidal volume on the breathing simulator to volumes slightly larger than one liter. Three different settings were tried to simulate three different purge rates.

Prior to start-up, the system was flushed with air. The oxygen concentration in the breathing gas was measured on a Beckman E2 Analyzer with samples taken from the inhalation line at the inlet to the breathing simulator. Readings were taken every minute during the run. The start-up procedure was as outlined above except that no oxygen bleed flow was used, therefore, all of the purge flow was through the vent valve. The results of these tests are shown in Figure 34.

It was found that these test results fitted very closely, the equation derived for a continuous bleed from a well-mixed container. This showed that the vent valve operation was consistent during these tests. A more rapid purge at start up could be achieved by opening the oxygen valve to the demand regulator a few seconds prior to donning the mask which would purge the system at a high rate through the mask. Another alternative would be to manually open an auxiliary purge valve after donning the mask and turning on the oxygen supply.

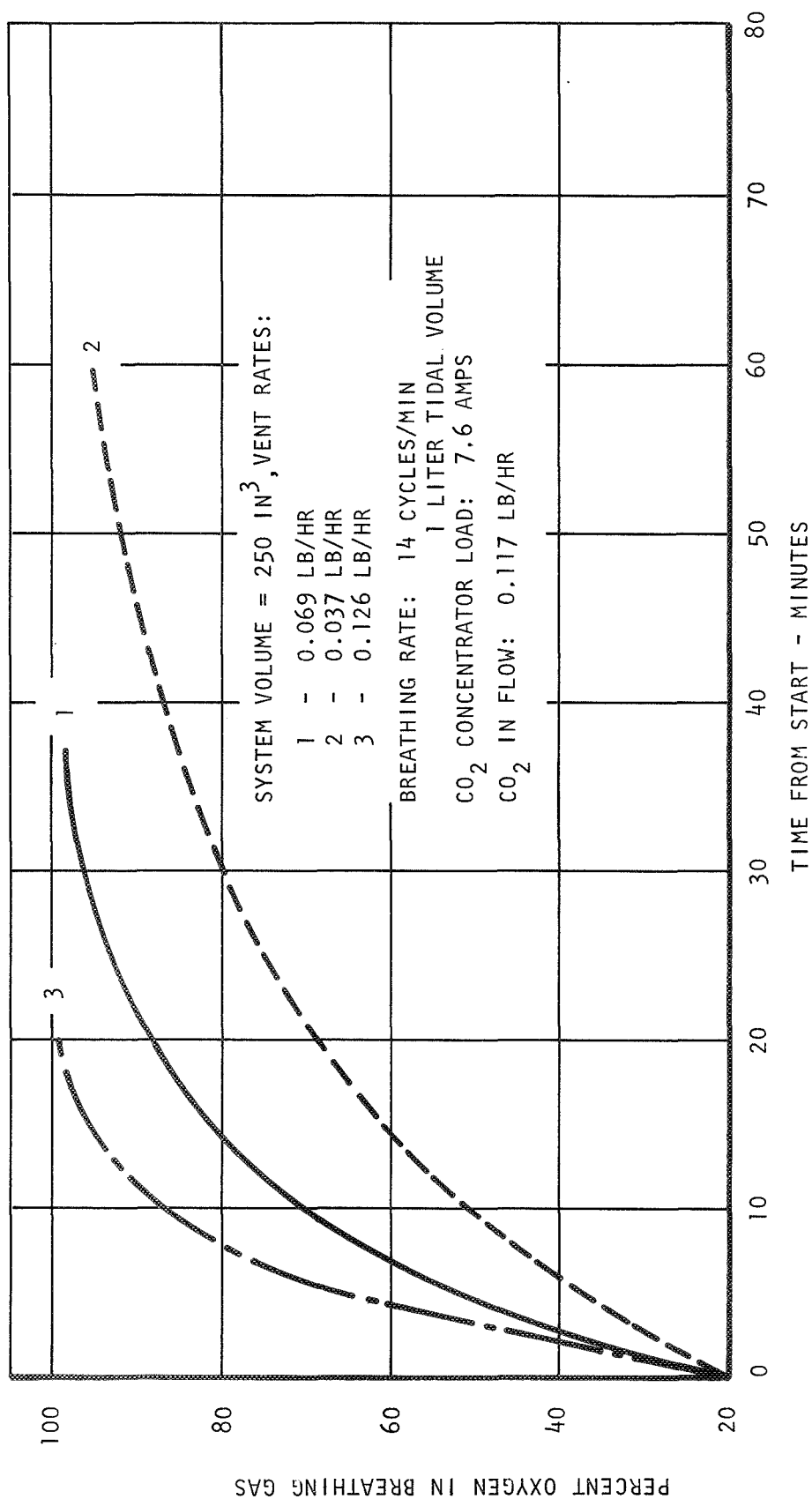


FIGURE 34 NAOS - BREADBOARD SYSTEM START-UP TRANSIENTS, NITROGEN VENT OPERATING

Steady-State Operation. - Several one-hour tests were conducted in order to determine the effect of breathing rate on the carbon dioxide level in the inhalation line. No trends were observed and in all cases the carbon dioxide partial pressure was at a safe level of between 2.0 and 7.6 mm Hg with most data near 4.0 mm Hg. Most of the data was at the design operating condition of 18 breaths/minute at a 0.78 liter tidal volume.

In all cases, carbon dioxide inflow was constant at 0.117 lb/hr and the oxygen bleed rate was constant at 0.10 lb/hr. The water coolant temperature to the dehumidifier was nearly constant at 53°F. The high effectiveness of the dehumidifier resulted in exit dew point temperatures near this value. The oxygen temperature at the inlet to the breathing machine reached temperatures equal to the ambient as was anticipated. Thus, at 70°F to 80°F, the relative humidity in the breathing gases was between 40 and 60 percent which is close to the desired 50 percent. Table X shows a summary of breadboard system operating conditions.

Operation of the breadboard was accomplished without operation of the oxygen circulating blower at the carbon dioxide concentrator. This was done to determine if the breathing flowrates were sufficient to cause the transfer of carbon dioxide in the concentrator at low carbon dioxide partial pressures. In this case, the effect of breathing rate is apparent since this is the flow rate through the carbon dioxide concentrator. With the blower operating, however, the nominal breathing rates of 0.5 CFM would have little effect when superimposed on the blower flow of 3 CFM. Figure 35 shows the results obtained without the blower operating.

At the low flowrate, the carbon dioxide level rises but is quite safe and levels out. Increasing the breathing rate lowers the carbon dioxide concentration. At the end of the third hour of operation, the carbon dioxide concentrator experienced a crossleak between the hydrogen and oxygen sides resulting in rising cell temperatures necessitating shutting down the system.

The crossleak was attributed to drying out of the cells at the oxygen inlet end. This would be caused by the relatively dry ( $\sim 55^{\circ}\text{F}$  dew point) oxygen entering the concentrator. This may not occur in actual application due to the high humidity of exhaled breathing gases with a dew point of 98°F. Crossleakage is less likely to occur while operating with the blower since the dry gases are mixed with a much larger flow rate of gases in equilibrium with the carbon dioxide concentrator.

This test did show that respiration flows alone, are sufficient to operate the carbon dioxide concentrator and maintain safe levels of carbon dioxide in the rebreather loop. This indicates that it may be possible to eliminate the blower and circulating loop from the system. If the blower is retained for the humidification consideration and/or to make breathing easier, then a blower failure is not an emergency situation since up to three hours of system operation have been demonstrated without blower operation.

The total operating time was 103.5 hours. This represents over 100,000 breathing cycles on the system and is approaching the range of present oxygen equipment life requirements.

TABLE X

NAOS LABORATORY BREADBOARD  
OPERATING CONDITIONS

O <sub>2</sub> Generation Rate	0.15 lb/hr
O <sub>2</sub> Generation Pressure	73 psia
CO <sub>2</sub> Concentrator Current	7.6 amps
Breathing Simulation:	
Respiration Rate	10-30 cycles/min
Tidal Volume	0.5-1.0 liter
O <sub>2</sub> Bleed	0.10 lb/hr
CO <sub>2</sub> Inflow	0.117 lb/hr
Breathing Gas Delivered at:	
Temperature	70°F-80°F
Relative Humidity	40%-60%
Total Pressure	1 atm.
CO <sub>2</sub> Partial Pressure	2.0-7.6mm Hg
Operating Time	105.4 hrs
Number of Start-Ups	29
Longest Continuous Run	8.2 hrs

BREATHING SIMULATOR TIDAL VOLUME: 0.78 LITERS  
 CO<sub>2</sub> IN FLOW RATE: 0.117 LB/HR  
 CO<sub>2</sub> CONCENTRATOR CURRENT: 7.6 AMPS

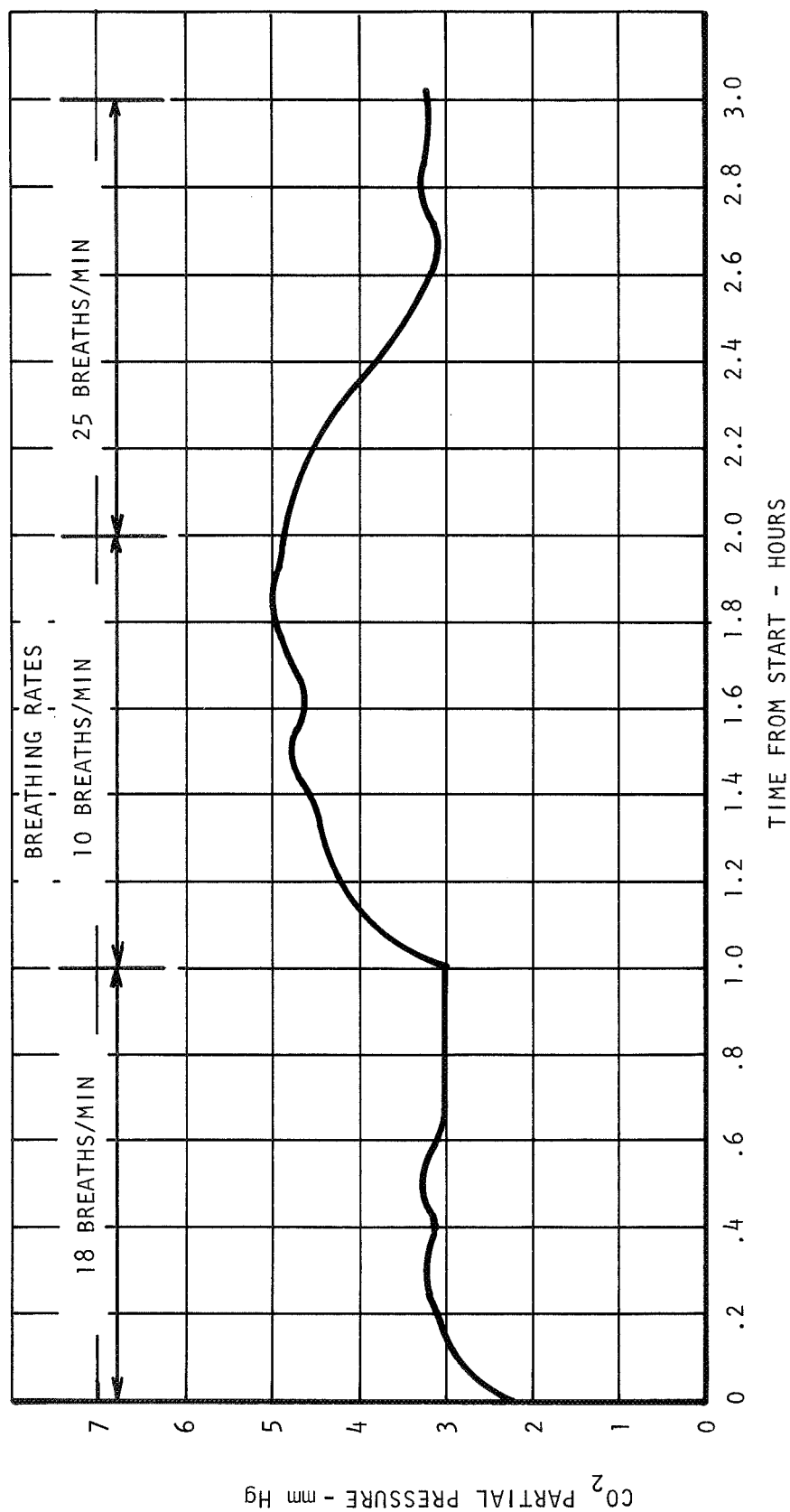


FIGURE 35 NAOS LABORATORY BREADBOARD OPERATION WITHOUT O<sub>2</sub> CIRCULATING BLOWER

Several tests were conducted to determine the capacity of the carbon dioxide concentrator to absorb carbon dioxide in the event of a power failure where no hydrogen flow is available and the circulating blower stops. The tests showed that the concentrator has essentially no capacity as might be expected since the electrolyte volume is very small. If the system is to remain in operation during a power failure, two options are available.

The first would be to switch to open loop operation using oxygen from an accumulator. The second would be to continue using the rebreather but emergency power would be required to power the carbon dioxide concentrator. About 100 watts of DC power would enable the concentrator to operate if hydrogen were not available.

### High Capacity Water Electrolysis Subsystem

Water Electrolysis Module. - The Laboratory Breadboard System (LBS) as originally designed and using a typical ten-cell water electrolysis module could deliver 0.15 lbs oxygen per hour (100 amps/ft<sup>2</sup>) with peak loads of up to 0.18 lbs oxygen per hour. To increase this system's capacity to deliver 0.20 lbs oxygen per hour continuously with peak loads of 0.33 lbs oxygen per hour required modification of both electrolysis module and the LBS test rig. The original design of the water electrolysis module had demonstrated a capability to operate at 150 amps/ft<sup>2</sup> while maintaining a relatively stable performance level.

In order to fulfill the new LBS requirements, the use of an original module would most likely result in high power requirements (high voltage levels). A module having more than ten cells (i.e., reducing current density) or an improved cell configuration would be required to keep the power requirements low. Based on separate experiments, the latter approach was chosen. The ground rules for cell configuration modification were such that no major cell component modification should be required.

One of the limiting factors to higher current densities in static water-feed cells is the water transport from the feed matrix to the cell matrix. One of the ways to increase this feed rate is to allow a maximum possible, cross-sectional area across which the water vapor can diffuse. Original NAOS cell construction utilized a slotted current collector immediately adjacent to the water feed cavity. These slots blocked approximately 38 percent of the cross-sectional area. Hence, by removing the supporting ribs from the current collector, an increase in water feed capability could be attained. The loss in heat removal rate due to rib removal is insignificant since most of the cell overvoltage, hence heat load, occurs at the anode.

A new cell utilizing this construction principle was designed. A cross-section through the manifold area of such a typical cell is shown in Figure 36. Table XI identifies the numbered components. The hydrogen side current collector, Item 16, in the modified cell has a rectangular opening equal to the active cell area machined in its center. Since its heat removal function is minor, nickel sheet instead of nickel plated copper could be used. The hydrogen cavity spacer, Item 12, was increased from a 0.060" to 0.092" thickness to compensate for the missing current collector ribs.

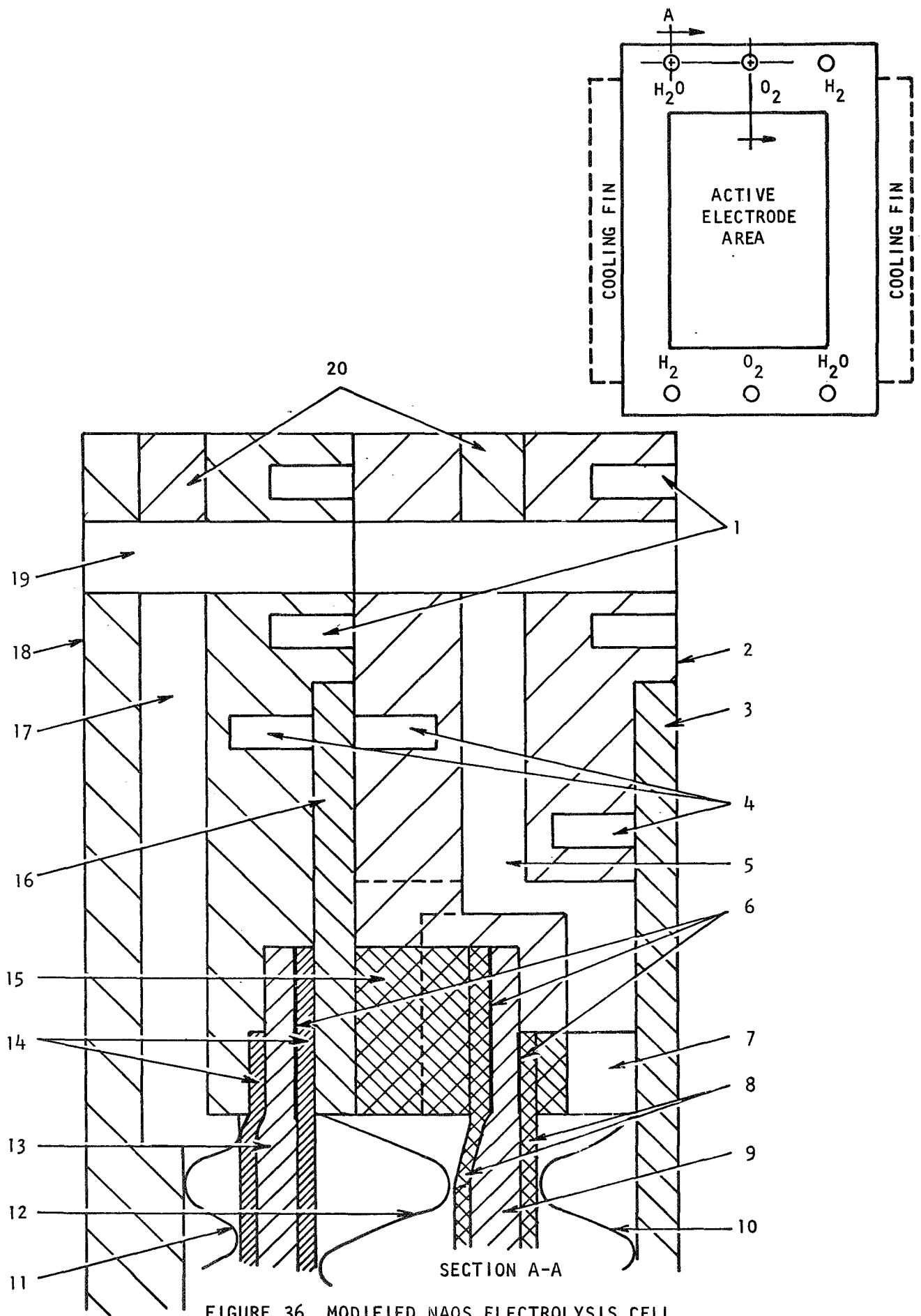


TABLE XI

## ELECTROLYSIS CELL COMPONENTS

<u>Item</u>		
1	Manifold O-Rings	Ethylene Propylene
2	H <sub>2</sub> - O <sub>2</sub> Frame	Polysulfone
3	Current Collector, Plain	Nickel-Plated Copper
4	Cavity Sealing O-Rings	Ethylene Propylene
5	O <sub>2</sub> Port Hole	N/A
6	Insulating Tape	Teflon
7	O <sub>2</sub> Compression Ring	Nickel
8	Electrodes	AB-6
9	Cell Matrix	0.030" Asbestos
10	O <sub>2</sub> Cavity Spacer	Expanded Nickel, 0.060"
11	H <sub>2</sub> O Cavity Spacer	12 Mesh, .020" Threads, Polypropylene Screen
12	H <sub>2</sub> Cavity Spacer	Expanded Nickel, 0.092"
13	Feed Matrix	0.030" Asbestos
14	Feed Matrix Support Screens	ASTM #70 Mesh, Polypropylene Screen
15	H <sub>2</sub> Compression Ring	Nickel
16	Current Collector	Nickel
17	H <sub>2</sub> O Feed Passage	N/A
18	H <sub>2</sub> O Cavity Plate	Polysulfone
19	Gas or Liquid Manifold	N/A
20	Plug	Polysulfone



The feed matrix, Item 13, was increased from 15-mil to 30-mil thickness. This increase in thickness, however, tends to increase resistance to water diffusion and hence water feed rate to the cell. It is felt that this decrease in feed rate is more than offset by the increase due to the increase in cross-sectional area. The thicker feed matrix makes for a more rugged cell construction which is especially desirable when a breathing function is coupled with the oxygen consumption. During such an operation, pressure fluctuations caused by periodic oxygen consumption causes flexing of the feed matrix. The 10-mil polysulfone slotted spacer that is used in the original cell design between the slotted current collector, Item 16, and the matrix support screen, Item 14, was eliminated from the modified cell construction. The increase in feed matrix thickness compensated for the loss of the spacer.

A spot-welding technique was used where practical to assemble the internal metallic parts. This tends to eliminate contact resistance. The hydrogen cavity spacer, Item 12, the cathode electrode, Item 8, the hydrogen compression ring, Item 15, and the hydrogen side current collector were spot-welded to each other. On the anode side, only the oxygen cavity spacer, Item 10, the anode electrode, Item 8, and the oxygen compression ring, Item 7, were spot-welded together. This subassembly could not, however, be spot-welded to the plain current collector, Item 3, since spot-welding to the nickel-plated copper would cause pitting with subsequent corrosion problems. A ten-cell module designated WEM #5 was assembled using the modified cell configuration.

Power Conditioning. - To generate 0.33 lbs oxygen per hour requires 50 amps. The power supply and electronic pressure control system of the laboratory breadboard test rig as originally designed could not supply this current level. The power conditioner for the WES module used four power transistor switch circuits in parallel to provide the 27 amps required, the flight breadboard power conditioner used higher current devices and only required two power transistor switches in parallel for 30 amps. Since then, even higher current devices have become available and these were used to uprate the laboratory breadboard power conditioner. With these new transistors, only one is required for a 30 amp conditioner. To provide a 50 amp power conditioner, two of the new power transistors were used.

To keep the rework at a minimum and to make use of readily obtainable off-the-shelf components, the 50 amp power conditioner power stage and filter was designed and built as two 25 amp systems in parallel as shown in Figure 37.

The identical power switch and filter circuit as used previously has been retained for each of the two parallel stages. The current measuring shunt was changed to a higher current capacity (lower resistance) unit. This allowed the control logic circuit to be retained with no changes.

Subsystem Tests. - WEM #5 was installed into the modified test rig and the operation of both the module and the test rig was verified at 50 amps (220 ASF). The initial stack voltage of the ten-cell module at 155°F, 30 psia and 220 amps/ft<sup>2</sup> was 19.2 volts. This voltage level increased with time and leveled out after approximately one hour at 22.4 volts.

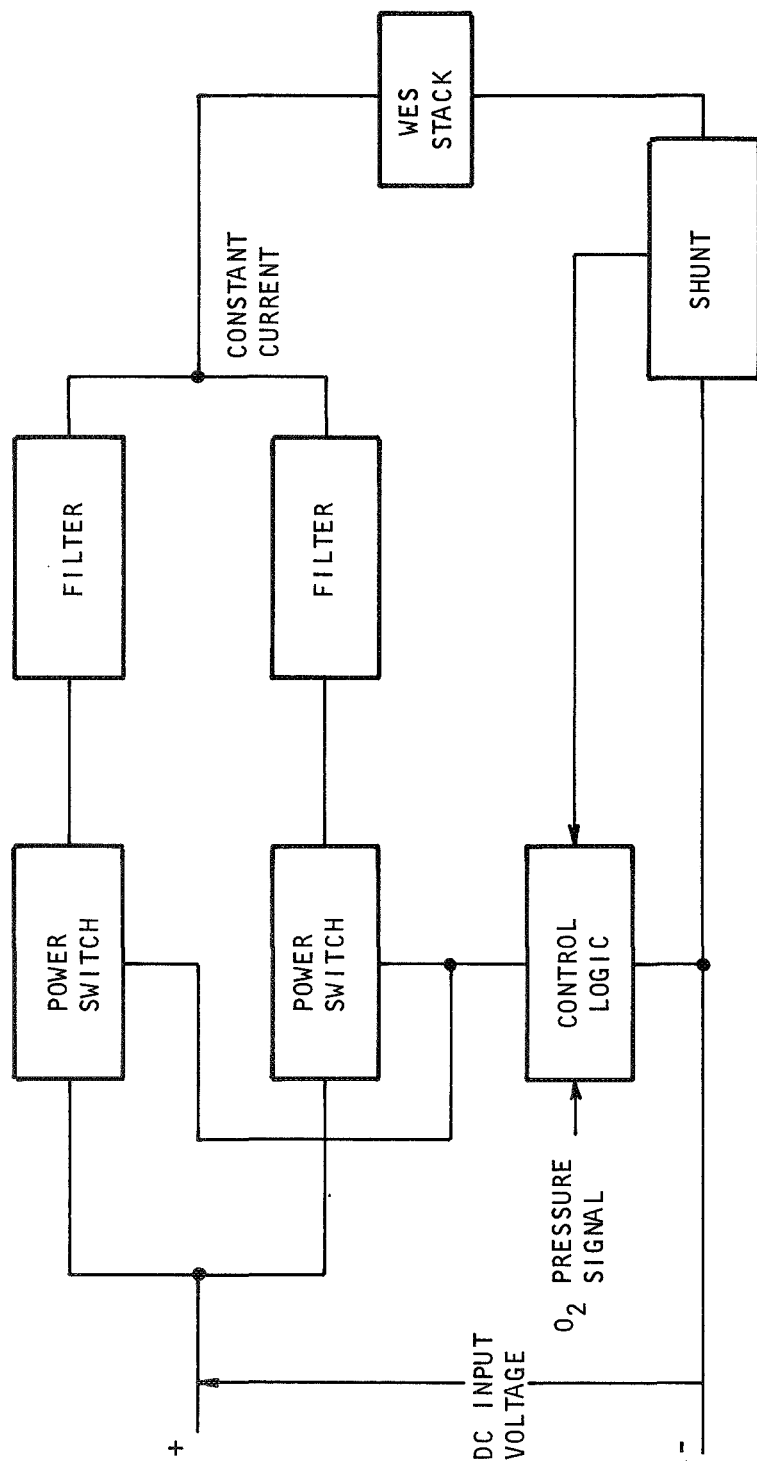


FIGURE 37 POWER STAGE AND FILTER FOR 50 AMP POWER CONDITIONER

The high capacity water electrolysis subsystem portion of the Laboratory Breadboard was operated as an open loop system. The oxygen outlet of the water electrolysis subsystem was connected to a CRU 68A diluter demand regulator. Automatic pressure control was used during this test to maintain the oxygen pressure at 50 psig independent of the oxygen demand rate. This control monitors the oxygen pressure by means of a pressure transducer and adjusts the electrical current into the electrolysis module to maintain this pressure. Using the regulator in a "normal oxygen" mode resulted in approximately 38 percent oxygen in the gas fed to the breathing mask. The oxygen generation rate of the electrolysis module was approximately 0.33 pounds per hour. The electrical current into the ten-cell electrolysis stack averaged 50 amperes. This corresponds to a current density of 220 amps/ft<sup>2</sup>. The measured stack voltage was 20 volts or 2 volts per cell. The electrolysis module was air-cooled and operated between 150°F to 170°F. The temperature gradually increased with time due to the fact that the cooling system was designed to handle one-half of this load in a closed loop system. Figure 38 is a photograph taken during this test.

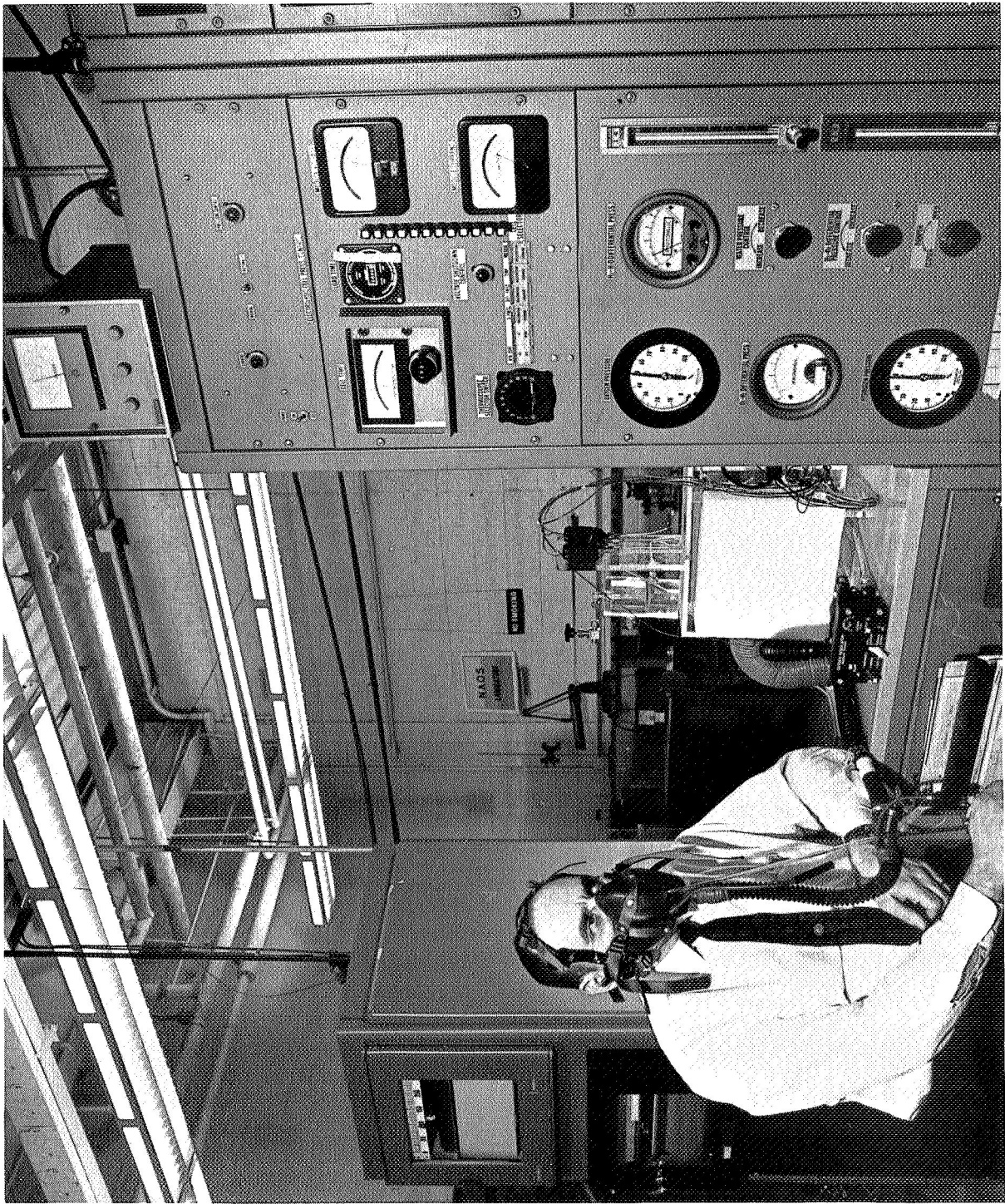


FIGURE 38 MANNED TEST OF OPEN LOOP O<sub>2</sub> GENERATOR

## CONCLUSIONS

1. The laboratory breadboard aircrew oxygen system meets the performance specifications.
2. No trends in the data were observable when operating the system over a range of breathing rates and tidal volumes.
3. Carbon dioxide partial pressure was always below the specified level of 7.6mm Hg with most of the data near 4.0mm Hg indicating a possible spacecraft application for this device.
4. The electronics developed for automatic control of oxygen generation rate and for constant current through the concentrator perform satisfactorily.
5. The size and weight of a packaged prototype system is applicable to aircraft requirements.
6. Satisfactory operation of the system indicates that the system is feasible and can be developed into a prototype system.
7. The total operating time of over 100 hours represents over 100,000 breathing cycles which is approaching the range of present oxygen equipment life requirements.
8. The laboratory breadboard is a useful and versatile apparatus allowing a wide range of operating conditions.
9. The subsystems can be operated independently if required. The breadboard can also be easily modified by adding or changing components due to its physical layout.
10. The operation of the water electrolysis subsystem as an oxygen generator in an open loop mode illustrates the simplicity of this method of oxygen generation for open loop as well as closed loop systems.

## RECOMMENDATIONS

1. The laboratory breadboard system should be maintained for use as a versatile test stand for a wide variety of investigations.
2. Continued development of the water electrolysis and the carbon dioxide concentrator subsystems is recommended for use in numerous applications involving separate or combined use of these devices.
3. The simplicity of the water electrolysis subsystem and its independence of the environment warrants considering this method of oxygen generation for open loop oxygen systems.
4. The satisfactory performance of the carbon dioxide concentrator as a steady-state carbon dioxide removal device for long term continuous operation has been demonstrated. Its use in other life support applications should be considered.
5. The satisfactory operation to performance specifications shows that the NAOS system is feasible and that further development is warranted towards specific applications.

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